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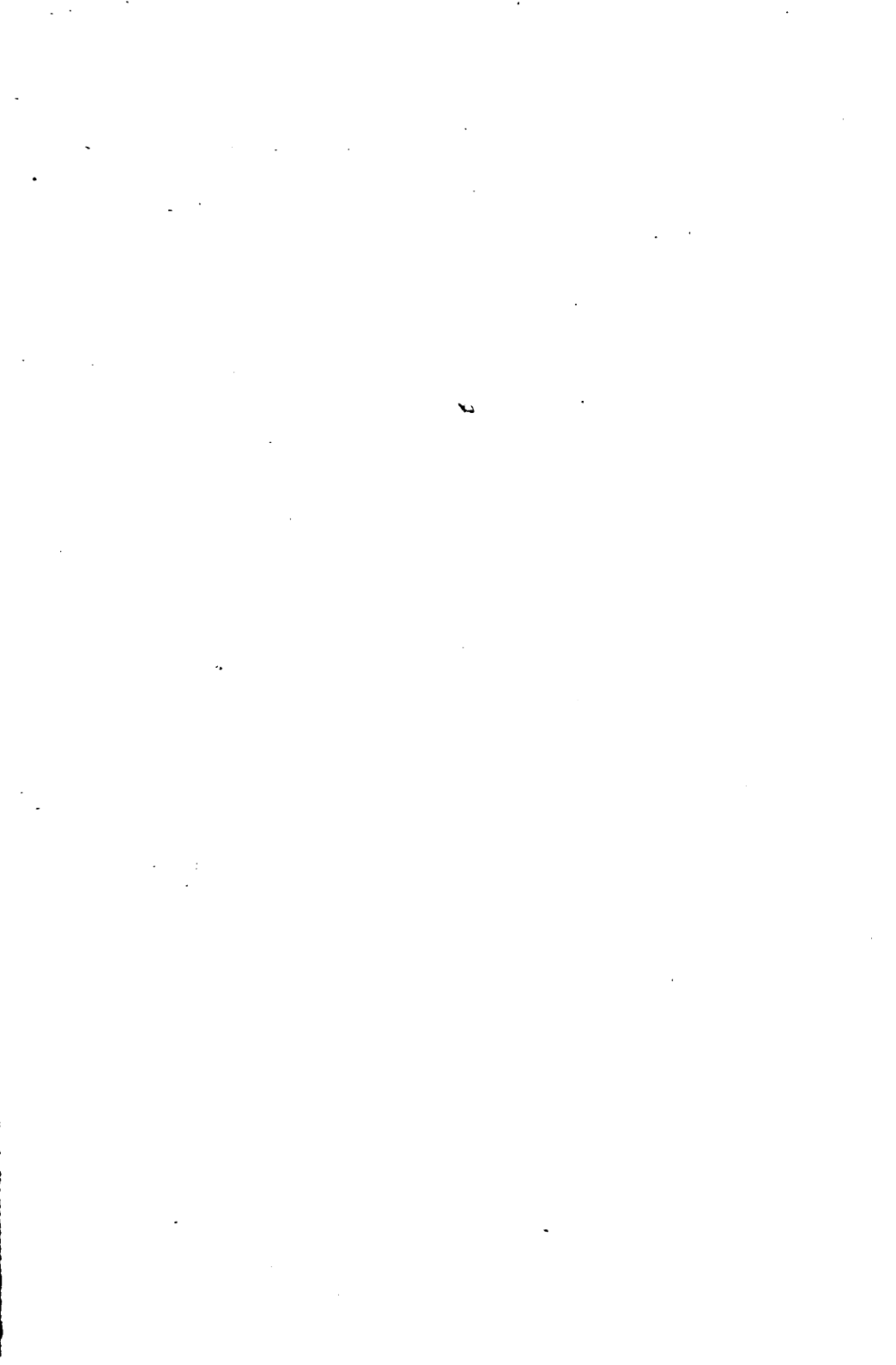
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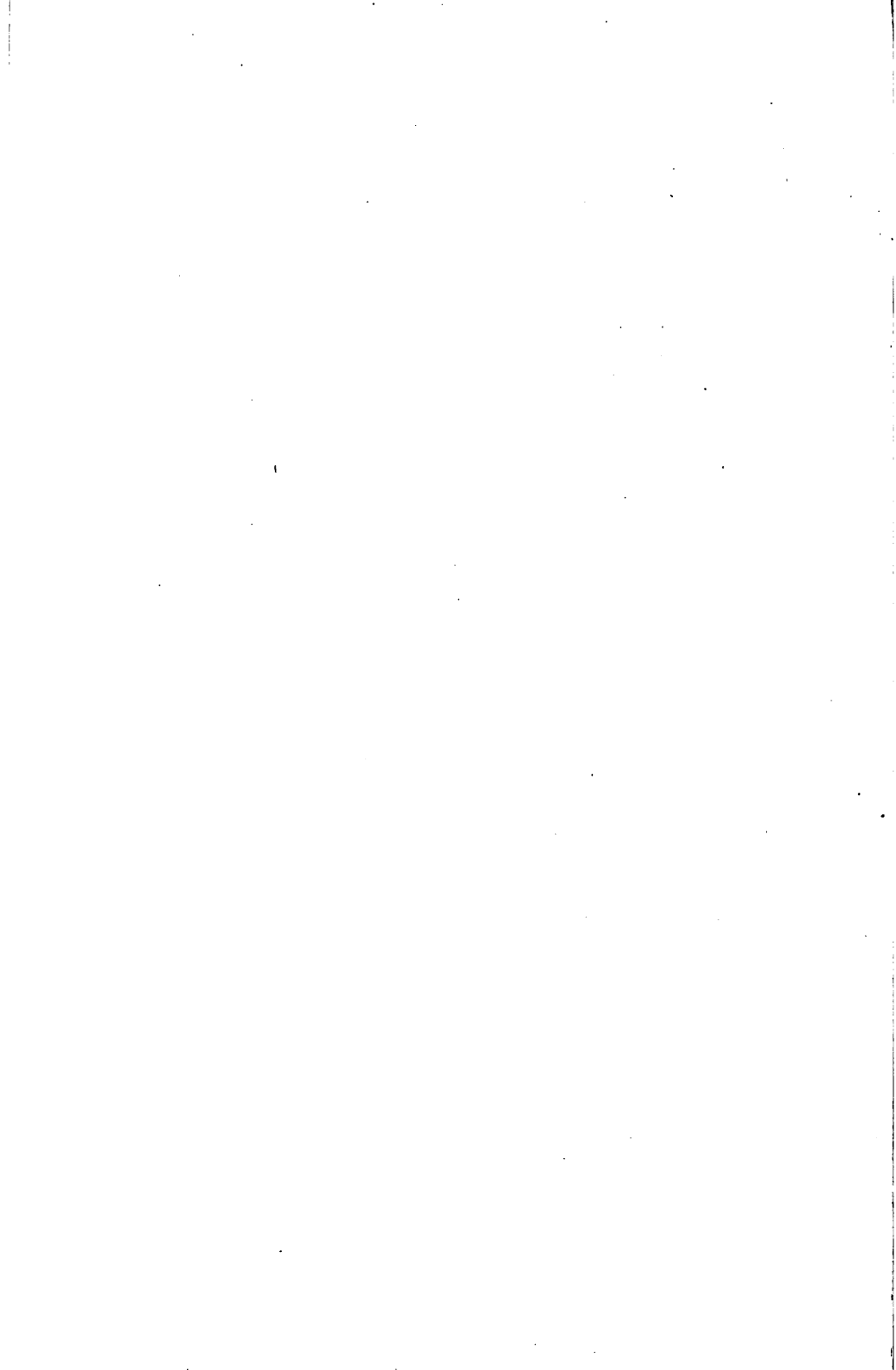
ROCK

TUNNELS

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ROCK BLASTING

THE
BLASTING OF ROCK

IN
MINES, QUARRIES, TUNNELS,
ETC.

A SCIENTIFIC AND PRACTICAL TREATISE FOR
*THE USE OF ENGINEERS AND OTHERS ENGAGED IN
MINING, QUARRYING, TUNNELLING, &c., AND FOR
MINING AND ENGINEERING STUDENTS*

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PART I.

*THE PRINCIPLES OF ROCK BLASTING AND
THEIR GENERAL APPLICATION*

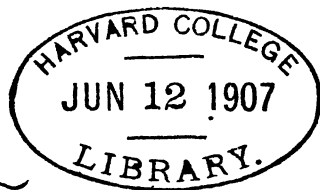
WITH NINETY ILLUSTRATIONS

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P R E F A C E.

THE present work is based on the results of a large number of experiments, which were carried out by us about three years ago, with the object to discover the true principle of the resistance of rock to a blast, respecting which further researches were necessary in consequence of the rules and formulæ usually met with in works on rock blasting proving to be very erroneous when applied to the ordinary blasting operations of mining, tunnelling, &c.

This work is, therefore, an attempt to supply the need of a correct theory, with reliable rules and formulæ for the necessary calculations, the information on explosives, fuses, &c., being added to make the work complete in itself. The correctness of the rules and formulæ is demonstrated by the results of a series of blasting experiments, and by the theory on which they are based being quite in accord with true mechanical principles.

It is a remarkable fact that the theories of rock blasting which have been generally adopted, do not take into account the influence of the form of the chamber employed, seeing that the initial force of the blast, and the resistance of the rock will largely depend thereon for any direction of the line of resistance.

The methods by which the rules and formulæ were deduced are fully explained, and examples of all the more important calculations are given to assist the engineer to deal with any question that may arise in practice, especial attention being directed to how the greatest economy may be attained in the boring of holes and consumption of explosive.

The subject may be appropriately divided into two parts, viz. (1) the principles and their general application, and (2) appliances for drilling the shot-holes, and methods of blasting in mines, quarries, tunnels and subaqueous operations. We have therefore treated it under these headings, this volume comprising the first part, whereas the second part will be published in a second volume which is in preparation.

Valuable practical information is given on the

most useful and economical explosives, and on detonators, electric fuses and electric exploders, for which we have much pleasure in acknowledging our obligations to Messrs. NOBEL'S EXPLOSIVES CO., LIMITED; Messrs. THE COTTON POWDER CO.; Messrs. CURTIS AND HARVEY; and Messrs. SIEMENS BROS. AND CO., LIMITED. We are also greatly indebted to Messrs. BICKFORD, SMITH AND CO. for information respecting their fuses.

The information on electric blasting agrees with the results obtained in our experience, and will, we believe, be found very useful.

A number of Tables are added to facilitate the calculations.

The present volume, though only the first instalment of the work, is complete in itself, and we believe it will be found to give the essential information for carrying out economical and systematic blasting operations. To render it more useful an Index is added which has been carefully prepared.

It will be a source of great pleasure and satisfaction to us if we have accomplished the purposes for which this work was undertaken, namely, to give the Engineer, Miner and Quarryman a correct

theory of rock blasting as well as a useful counsellor in questions of application ; to the teacher of the science a serviceable text-book for instruction ; and to the student of mining and quarrying a welcome aid in the study of blasting.

ALBERT W. DAW.

ZACHARIAS W. DAW.

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THE
PRINCIPLES OF ROCK BLASTING
AND
THEIR GENERAL APPLICATION.

CHAPTER I.

PRELIMINARY REMARKS.

1. *Rock Blasting* is the science of splitting or loosening rock by means of explosives applied in holes or chambers in the rock.

2. *Failure of previous Rules for Rock Blasting.* Many books have been written on the science for the guidance of the practical man, but it may be said that they all fail to give the most essential information for the determination of the size and position of the chambers and weight of charge. With regard thereto, Mr. George F. Harris, F.G.S., in his work on 'Granite and our Granite Industries,' says:

"In reading works on the subject one frequently sees a great deal about rules for determining the quantity of powder to be used in blasting, direction of the holes, &c., which theoretically are all very

well ; but the most of them in practice will not work. They nearly all assume that the rock to be blasted is a firm solid body without any cracks, &c., whilst the peculiar conditions in which holes would have to be bored to follow out the rules would waste too much time, and cost too much money to be of real advantage. As a matter of fact, before a hole is bored for the blast, a good quarrymaster looks at the block to be removed, and endeavours to find all cracks and joints. He then sees whether the mass has to be blown up the bed or against it, and observes the manner in which it may be wedged in by other blocks. After mature consideration he instructs the men under him to bore the hole, and estimates the quantity of powder to be used, not by the depth of the hole, but by judging the amount of force required to move the block. Experience has taught him how to do this."

Now, the quarryman's experience is the ascertained result of series of trials and experiments ; that is to say, he knows approximately the best position and size of hole, and the quantity of explosive required for a given blast, from the results of similar shots, without, perhaps, much knowledge of the fundamental principles governing the different conditions which obtain in blasting, but which, if understood by him, should enable him to attain still greater economy in his work.

Such, then, being the result of experience, it

becomes most important to study the principles involved more carefully in order to ascertain wherein the cause of the erroneous results consists. In the present work, therefore, rules or formulæ are worked out on well-known mechanical principles so as to be applicable to all the varied conditions of the rock and charge, and by means of which any question as to the size and position of chamber and quantity of charge to be employed may be answered ; whilst the causes of the failure of the rules given in works on the subject are amply demonstrated. A great deal of useful information is also given regarding explosives and fuses, and the operations of rock blasting.

3. *The Operations of Rock Blasting* consist (1) in boring, mining or excavating suitable holes or chambers in the rock to be blasted ; (2) in inserting a charge of some explosive compound therein ; (3) in filling up the whole or part of the remaining portion of the hole with suitable material ; (4) in igniting or detonating the charge to cause its explosion. The second operation is called charging, the third tamping, and the fourth firing.

4. *Effect of a Blast.*—By the explosion of the charge there is a sudden development of gas of high tension, which exerts a great pressure or shock upon the walls of the chamber, and if such pressure or shock is greater than the resistance of the rock to rupture, the rock is loosened or projected according to the strength of the charge.

5. *Conditions that influence a Blast.*—From experience and theoretical considerations we learn that the effect of a blast may be influenced by—

- (a) The shape in which the rock is presented, or the size and number of free faces.
- (b) The tenacity or cohesive strength of the rock.
- (c) The structure of the rock as to whether it is laminated, stratified or fissured, and the position, direction and number of the joints.
- (d) The strength and nature of the explosive compound.
- (e) The size and form of the chamber.
- (f) The character of the fuse, and tamping.
- (g) The thermal conductivity of the rock.
- (h) Whether the blast is to act alone or simultaneously with or following others.
- (i) The angle of the line of resistance with the horizon.
- (j) The specific gravity of the rock.

6. *Form of Cavity produced in Homogeneous Rock.*—In Fig. 1, the crater abc represents the general form of cavity produced by the action of a blast at a point b in homogeneous rock when there is only one free face ac , the angle abc varying generally between the limits 90° – 120° , according to the structure of the rock and strength of charge employed. The form of the cavity, as will be explained further on, depends on the form of the chamber, or

the projection of its pressure surface at right angles to the line of resistance. For instance, if this is circular the crater formed by the blast will be the frustum of a cone ; and if a square, the frustum of a pyramid—that is, if not modified by any irregularities (joints or fissures) in the structure of the rock, or there being more than one free face. A free face is the exposed surface of any one side of a mass of rock.

7. *Quarrying of Rock.*—Experience shows that rock is most economically and conveniently mined

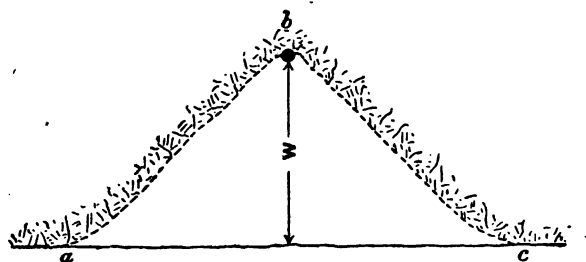


FIG. 1.

or quarried in steps or benches with straight and vertical walls, and that the height of such steps depends on the depth and diameter adopted for the boreholes.

8. *Formula for Determination of Charge.*—According to works on rock blasting, the calculation of the charge required at *b*, Fig. 1, for a line of resistance *W* should be made according to the following formula :—

$$L = C W^3,$$

in which L represents the weight of charge, W the shortest distance from the charge to the free face, and C the charging coefficient. A necessary condition, however, for the application of this formula is that the chamber be properly proportioned to the resistance of the rock.

9. *Previous Theories of Rock Blasting*.—As the basis for the above formula, the following theories are given by Andrée and Guttman:—

(a) “As homogeneous matter varies as the cube of any similar line between them, charges of explosive capable of producing the same effects are to each other as the cubes of the line of least resistance.”—*Andrée*.

(b) “When a charge is concentrated at a mathematical point in the centre of an unlimited and easily compressible mass its conversion into gas by firing will enlarge the space originally occupied by the explosive into a spherical cavity, and hence it follows that the quantity of a concentrated charge has a direct ratio to the sphere affected by the explosion; or as spheres vary as the third power of their ratio, and the line of least resistance in rock may be taken as proportional to the radius of explosion, it therefore follows that the charge, under like conditions, will vary as the third power of the line of least resistance.

“ Extended charges may be considered as an interrupted series of concentrated charges each of which will have its own sphere of action, and as these spheres intersect and reinforce one another the cavity produced by their continued action will be ellipsoidal, the mutual reinforcement being greatest at the centre of the charge.”—

Oscar Guttman.

10. *Objections to the above Theories.*—With regard to these theories, there appear at once the following three serious objections to them: First, they do not take into account the cohesive strength or principal resistance of most rocks; secondly, they entirely neglect the influence of the size and form of the chamber on which the initial force of the explosive and the resistance of the rock to rupture depend; and thirdly, they ignore the fact that the resistance due to the mass is affected by the direction of rupture; for if from above downward the weight of the mass will be a force assisting rupture, and the reverse if from below upwards, or when directly opposed to gravity. Excepting, therefore, as stating a single relation of the charge to the resistance, which is true under special conditions, these theories may be said to be totally misleading.

CHAPTER II.

ON THE RESISTANCES IN ROCK BLASTING.

11. There are the following three distinct resistances to a blast :—

- (a) A resistance due to the cohesion of the rock.
- (b) A resistance due to the mass or weight of the rock.
- (c) A resistance due to the hanging of the rock loosened by the blast along the lines of fracture.

12. *Influence of Mode of Application of Force.*—The force required to produce rupture of a given section of rock, as, for instance, the section *abc* (Fig. 1), will depend on the mode of application of the force, as, according to the laws of mechanics, rupture will take place by shearing when the points of application of the force coincide with the surface of separation, and, on the contrary, by flexure when the arm of the force is of sufficient length to allow of a bending of the mass, and the force is not very suddenly applied.

13. *Force of an Explosion in a Chamber conducive to Rupture by Shearing.*—If we suppose Figs. 2 and 3 to represent the section of a mass of rock with a

free face A B, and to contain a short cylindrical chamber C D, having a charge filling the chamber, and such charge to be exploded, the gases thereby

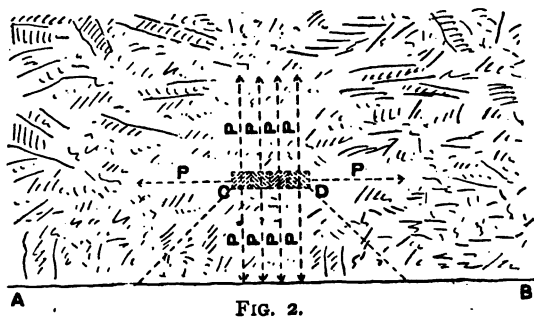


FIG. 2.

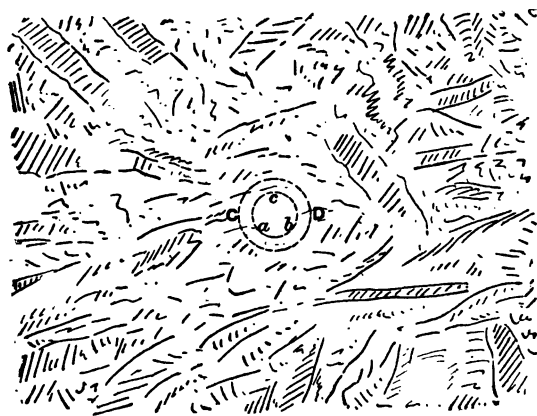


FIG. 3.

generated will develop a number of equal forces P acting on each unit of the surface of the chamber, and each on the side of the free face A B, tending to rupture the rock in the direction of the free face

A B, whereas the pressure of the gases on the other sides are neutralised by the resistance of the rock. The centre of pressure of these forces is the circular line *abc* (Fig. 3), whose radius is two-thirds of the radius of the chamber C D, one-third of which may be taken as the arm of the force; as experience shows that the line of fracture produced by a blast in homogeneous and compact rock, when there is only one free face, invariably commences at the limit of the surface on which the gaseous pressure is exerted. The arm of the total force acting on the centre of pressure is, therefore, very short for rupture by flexure, and as it is still shorter for any other form of chamber offering the same pressure area to the gases, the conditions are evidently more favourable for rupture by shearing than by flexure, the shearing action of the force being also promoted by its sudden application and the inelastic nature of rock.

14. *Force required to produce Rupture by Shearing.*—According to the laws of mechanics, if rupture takes place by shearing and S denotes the periphery of the chamber, W the line of resistance, and K_1 the modulus of shearing, we can put for the force P required to produce rupture

$$P = S W K_1.$$

15. *Experiments on Resistance of Ice to Rupture.*—The formula $P = S W K_1$ might be verified by bursting specimens of homogeneous rock by

mechanical means ; but as we may assume that the laws governing the resistance of one inelastic body are the same as for another, it is advantageous to substitute ice for this purpose, as it is homogeneous and easily worked into any desired form. In accordance with this view, we have experimented with ice with the mean results tabulated below. Blocks varying from 4 to 8 inches thick were taken

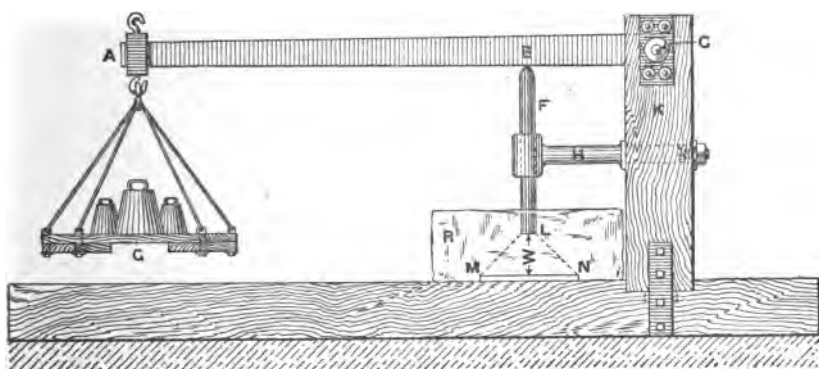


FIG. 4.

for the experiments, which were carried out with the apparatus illustrated in Fig. 4.

In Fig. 4, A B C is a steel lever of the second kind, pivoted at C to the bracket K, and having a scale G, a steel bar F working in the guide H for transmitting pressure to the block of ice R, this arrangement being adopted to ensure a perpendicular pressure being kept on the block at L ; M N the free face, and W the thickness of ice ruptured.

The size of the bar at L, thickness of ice ruptured, and size and form of the free face were varied as given in the table. The weight due to the lever was determined by weighing and calculation.

In the experiments very homogeneous ice without any apparent flaws was used, and every care was taken to insure the proper working of the testing apparatus, and that the means of measuring the force exerted in producing rupture was correct. During the experiments the temperature varied between $+2^{\circ}$ and -5° Celsius, which may have affected the relative accuracy of the results slightly, but we think to a much smaller extent than any difference in the structure of the ice itself.

The very satisfactory agreement between the results obtained for the modulus of rupture K_1 , found by dividing the pressure required to produce rupture by the product of the thickness of ice ruptured and periphery of the pressure surface, establishes, we think, beyond question the theory that rupture takes place by shearing, as the slight discrepancies in the results may be taken as due to irregularities in the structure and cohesive strength of the ice used for the experiments, and inaccuracies due to faulty arrangement, friction, &c., of the apparatus. Further experiments are necessary to ascertain the influence of the angle of fracture, which seems to affect the resistance to rupture slightly. In rock, the angle of fracture is affected

TABLE OF EXPERIMENTS ON RESISTANCE OF ICE TO RUPTURE.

Number of Experiments.	Number of Free Faces.	Shape of Free Face.	Diameter or length and breadth of Free Face.	Diameter or section of bar F.	Thickness of ice ruptured W.	Product of thickness of ice ruptured by breadth of bar F. S X W.	Form of Cavity produced.	Mean pressure required to produce rupture p.	Modulus of rupture K ₁ obtained by dividing pressure applied by product of thickness of ice ruptured and periphery of bar or pressure surface.
6	1	Circular	inches 3	inches 1	inches 1	3.14	Frustum of cone	kg. 167.1	53.22
6	1	"	3	1	1½	4.71	"	253.8	53.88
6	1	"	3	1	2	6.28	"	338.2	53.85
6	1	"	3	1	2½	7.85	"	422.3	53.80
6	1	"	4	1	1	3.14	"	157.7	50.22
6	1	"	4	1	1½	4.71	"	229.2	48.66
6	1	"	4	1	2	6.28	"	315.8	50.29
6	1	"	4	1	2½	7.85	"	393.7	50.15
6	1	"	4	1	3	9.42	"	473.8	50.30
4	1	"	6	2	2	12.56	"	610.6	48.62
4	1	"	6	2	3	18.84	"	910.7	48.34
4	1	"	6½	2½	2	15.70	"	744.0	47.40
3	1	Rectangular	3 X 6	3 X ½	1½	10.50	Frustum of pyramid	558.0	53.14
3	1	"	3 X 6	3 X ½	2	14.00	"	734.0	52.43
3	1	"	3 X 6	3 X ½	3	21.00	"	1097.7	52.28

by the greater facility with which it cleaves in one direction than in another. The weight of the ice ruptured is evidently very small, and may be neglected.

Calling the thicknesses of ice burst $W, W_1, W_2, W_3, \dots W_n$, the bursting pressures $P, P_1, P_2, P_3, \dots P_n$, and the peripheries of the pressure surfaces, $S, S_1, S_2, S_3, \dots S_n$, we have, according to the above table, very nearly

$$\frac{P}{S \times W} = \frac{P_1}{S_1 \times W_1} = \frac{P_2}{S_2 \times W_2} = \frac{P_3}{S_3 \times W_3} = \frac{P_n}{S_n \times W_n} = K_1$$

which agrees with the formula for shearing.

16. *Similarity between Cavities produced by Sudden and Gradual Application of Force.*—An important point to note in connection with these experiments is that the form of cavity produced by the application of gradual pressure is similar to that obtained by blasting in rock under similar conditions of free face and pressure surface, it being influenced in both cases by the form of the pressure surface at right angles to the direction of rupture; for instance, in homogeneous rock with one free face, a concentrated charge will produce a conical cavity, and an extended one an elongated trough.

17. *Force required to overcome the Cohesive Resistance of Rock when there is one or more Free Faces.*—In Figs. 5 and 6, plan and section, let M, M_1, N_1, N , represent the surface acted upon by a

blast in homogeneous rock ; then, if A B is a free face parallel thereto, M, M₁, N, N₁, E, E₁, F, F₁, will be

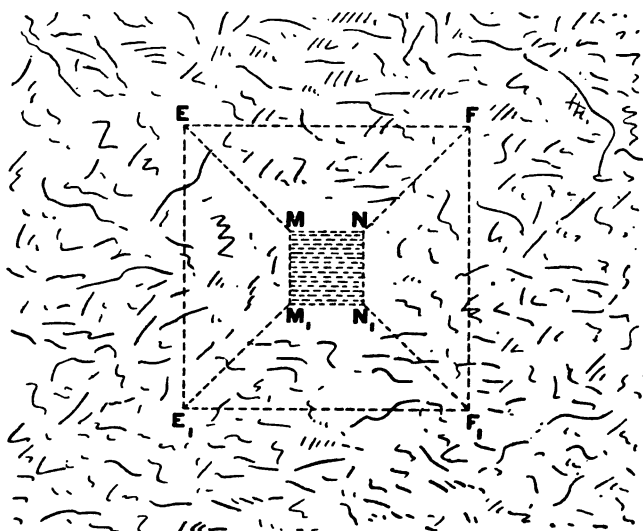


FIG. 5.

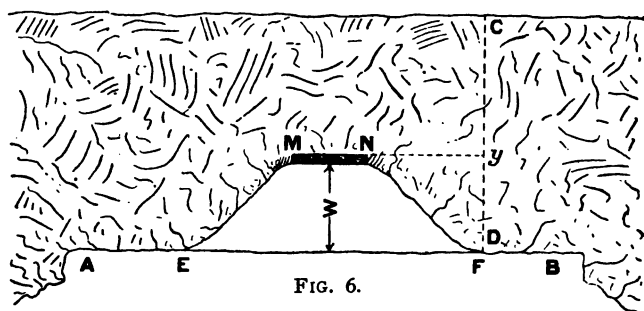


FIG. 6.

the limits of the rock loosened, if the area of the surface M, M₁, N, N₁, and the line of resistance W are properly proportioned to the strength of the

explosive. (It should be remarked that the corners at E, E_1, F, F_1 , will form a more or less irregular curve instead of right angles, as shown in the plan.) If we denote the periphery of the chamber M, M_1, N, N_1 , by S , the forces producing rupture by P , and distance between the chamber and the free face $A B$ by W , it is evident from the foregoing that the relations of these quantities will be expressed by the formula $P = S \times W \times K_1$. If there are two free faces, as in the case of a lateral free face along F, F_1 , Fig. 5, perpendicular to the free face $A B$, as shown by the dotted line $C D$ in Fig. 6, the formula $P = S \times W \times K_1$ will also obtain if we so regulate the distance of the chamber M, M_1, N, N_1 , from the free face $C D$, that the force required to produce rupture on the side $C D$ is approximately equal to the force required to produce rupture on each of the sides E, E_1, E, F , and E_1, F_1 .

It may happen that such equilibrium of the resistance of the rock on each side of the chamber exists when the free face $C D$ coincides with the limit of fracture F, F_1 , on the free face $A B$. The influence of the free face $C D$ in this case causes the detachment of the section of rock $N \gamma D$, with the mass $E M N F$ (Fig. 6). If there be free faces along the other limiting lines of fracture $E E_1, E F$, or $E_1 F_1$, parallel to the line of least resistance, the rock will be similarly fractured on each of these sides, as explained for the case of a free side along the

limiting line of fracture FF_1 . Therefore, for the same chamber in a projecting mass of rock with five free faces as represented in Figs. 7 and 8, if the line of resistance W is proportioned as above described, and the distances $M\gamma_1$, $N\gamma_2$, $N\gamma_1$, and $N_1\gamma_3$, are not

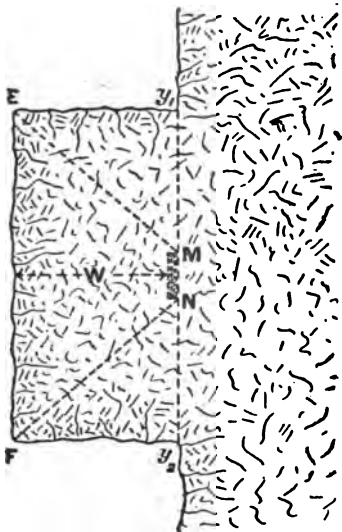


FIG. 7.

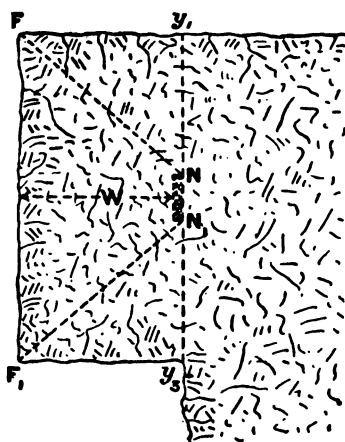


FIG. 8.

greater than W , the mass will be ruptured along the section $\gamma_1\gamma_2$, instead of the lines $EMNF$.

Another case is that of a block of rock detached on all sides as in the case of a freestone (Fig. 9), in which the sides EE_1 , E_1F_1 , FF_1 and EF correspond to the limiting lines of fracture in the cases before mentioned; hence the product of the line of least resistance and the periphery of the chamber

is also a measure of the resistance to rupture when there are six free faces.

The formula $P = S \times W \times K_1$ is therefore applicable to any number of free faces on the principle that the position of the charging chamber should be

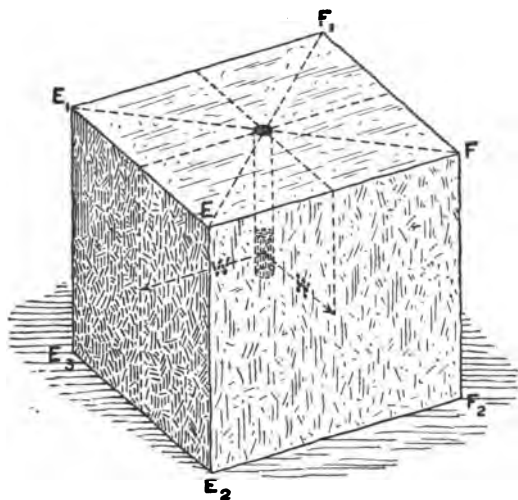


FIG. 9.

so adjusted that there is equilibrium of resistance on all sides of the line of resistance to rupture.

18. *The Resistances to Rupture and Shearing may be equalised.*—It is important to note that, owing to the inelastic nature of rock and the sudden application of the force, equal tension is produced in the rock, parallel to the line of resistance for any section that may be blasted, and that the resistance to rupture of the cross section $\gamma_1 \gamma_2$ (Fig. 7) may

be equal to the resistance to shearing under certain conditions which will be explained in the context. Assuming the rock to be absolutely inelastic, it is evident that we may put

$$R = F K$$

for the resistance of such cross section if F represent the area of the same and K the modulus of rupture of the rock ; and that we shall have $F K = S W K_1$, when R is equal to the resistance to shearing.

19. *The Section of Rock which may be ruptured is proportional to Periphery of Chamber for a given Line of Resistance.*—For a given line of resistance W , if the periphery of the chamber $M N$ be S , the force required to produce rupture by shearing is

$$P = S W K_1 ;$$

and if the periphery of projection of the chamber be S_1 , the force P_1 required to produce rupture is

$$P_1 = S_1 W K_1 ;$$

consequently,

$$\frac{P_1}{P} = \frac{S_1}{S}.$$

But as the force P is capable of breaking a cross section $F = C S W$, and therefore a force P_1 a cross section $F_1 = C S_1 W$, C being a coefficient,

$$\frac{P_1}{P} = \frac{F_1}{F} = \frac{S_1}{S}.$$

20. *Economy of Low Explosives.*—Hence it is clear that in homogeneous rock for any given line of resistance, the section of rock which a blast of any given strength will break is directly proportional to the periphery of projection of the charging chamber at right angles to the line of resistance. It is owing to this condition that the low explosives are sometimes employed in rock having comparatively small cohesive strength, or in the case of a mass of rock bounded laterally by free faces or joints, with greater economy than the high explosives. For instance, if the projecting mass of rock (Figs. 7 and 8) has a short line of resistance for the section $y_1 y_2$, then the proper charge of very strong explosive corresponding to such line of resistance applied at the centre of the mass would only break a conical cavity in the centre of the same; whilst an equally powerful charge of a weaker explosive, requiring a larger chamber and having consequently a longer periphery, would break down the whole mass.

21. *Resistance of the Mass after Rupture.*—After the rock is ruptured by the explosion of a charge applied in a suitable chamber therein, the gases produced will expand and enter the cracks and fissures formed in the rock, and the force of the blast will depend on the new surfaces resisting the free vent of the gases to the atmosphere, and the quantity of gases developed, or the weight of the charge. The resistance, on the contrary, will depend on the volume and specific gravity of the

rock to be moved, as also on the direction of movement; for, accordingly as the mass is moved from above downwards or from below upwards, the weight of the mass will be a force assisting or resisting the action of the blast, as in the one case the weight tends to assist, and in the other to resist the blast, such resistance varying as the sine of the angle of direction of movement with the horizon.

22. *Resistance of the Mass or Weight of Rock blasted at any Angle to the Horizon.*—In case the direction of the blast is upwards, we have to consider not only the resistance of cohesion but also that of the mass or weight of rock to be blasted, which is proportional to the product of its weight and the sine of the angle of movement to the horizon. The weight of the rock being G , and the angle of movement above the horizon a , we have

$$R = G \sin a.$$

If the direction of the angle a is below the horizon, the resistance R is turned into a force P , tending to produce rupture, and $P = G \sin a$.

Therefore, for a weight of rock G , and angles a and b of direction of blast above the horizon, the relation of the corresponding resistances R and R_1 (neglecting the resistance of cohesion) is

$$R : R_1 :: G \sin a : G \sin b.$$

$$\therefore \frac{R_1}{R} = \frac{\sin b}{\sin a}.$$

23. *Resistance of the Friction and Hanging of the Rock along the Line of Rupture.*—If there be friction and hanging of the mass of rock after rupture along the lines of fracture, and these resistances be taken as proportional to the mass of rock to be moved, and represented by a coefficient B, we have

$$R : R_1 :: G (B + \sin a) : G (B + \sin b),$$

whence

$$\frac{R_1}{R} = \frac{G (B + \sin b)}{G (B + \sin a)} = \frac{B + \sin b}{B + \sin a}.$$

For instance, if 50 per cent. more explosive were required for a vertical than for a horizontal blast (the quantity will depend on the effect to be produced), we shall have $\frac{R_1}{R} = 1\frac{1}{2}$ $\sin b = 1$ and $\sin a = 0$, and consequently

$$\frac{B + 1}{B} = 1\frac{1}{2}, \text{ whence } B = 2.$$

Substituting this value of B in the above formula we get

$$\frac{R_1}{R} = \frac{2 + \sin b}{2 + \sin a}.$$

If, then, we make R = the resistance for a horizontal blast $\sin a = 0$, and

$$\frac{R_1}{R} = \frac{2 + \sin b}{2} = 1 + \frac{\sin b}{2}.$$

Calling the charges which will overcome the resistances R and R_1 , L and L_1 , we have

$$\frac{L_1}{L} = 1 + \frac{\sin \delta}{2},$$

or

$$L_1 = \left(1 + \frac{\sin \delta}{2} \right) L.$$

If only 25 per cent. more explosive were required to give the desired effect we should have

$$L_1 = \left(1 + \frac{\sin \delta}{4} \right) L.$$

And in general, when $\frac{1}{n}$ th more explosive is required for a vertical than a horizontal blast,

$$L_1 = \left(1 + \frac{\sin \delta}{n} \right) L;$$

or, as $L = C_v W^3$ (Chapter III.), we have in general

$$L_1 = \left(1 + \frac{\sin \delta}{n} \right) C_v W^3.$$

24. *Combined Resistance of the Weight and Cohesion of Rock.*—When the resistance of the weight of the rock as well as the cohesive resistance of the same has to be considered in calculating the size and form of the chamber which, when filled with explosive, will overcome the total resistance to rupture, this is expressed by

$$R = (S \times W \times K_1) + G \sin \alpha,$$

S being the periphery of the chamber, W the line of resistance, K_1 the modulus of shearing of the rock, G the weight of the mass fractured, and a the angle of direction of the blast to the horizon.

Consequently, for any other values of these quantities we can put

$$R_1 = (S_1 \times W_1 \times K_1) + G_1 \sin a_1.$$

But the resistances R and R_1 are proportional to the areas of projections of the chambers at right angles to the line of resistance, and therefore

$$\frac{R_1}{R} = \frac{A_1}{A} = \frac{(S_1 \times W_1) + \frac{G_1 \sin a_1}{K_1}}{(S \times W) + \frac{G \sin a}{K_1}}.$$

25. *The Resistance of Cohesion of Rock to Rupture for any one Explosive varies as the Square of the Line of Resistance.*—For a line of resistance W and periphery S of blasting chamber, the resistance R to a blast is

$$R = S \times W \times K_1,$$

and for any other line of resistance W_1 ,

$$R_1 = S_1 \times W_1 \times K_1,$$

K_1 being the modulus of shearing of the rock.

Since, for boreholes whose diameter is d , the length of charge should be $m = n d$ (n being a coefficient of the diameter), $S = (2 n + 2) d$; and for

boreholes whose diameter is d_1 , $S_1 = (2n + 2) d_1$, we have

$$\frac{S_1}{S} = \frac{(2n + 2) d_1}{(2n + 2) d}.$$

Therefore, as $\frac{W_1}{W} = \frac{d_1}{d}$ (see Chapter V.),

$$\frac{R_1}{R} = \frac{W_1 \times W_1 \times K_1}{W \times W \times K_1} = \left(\frac{W_1}{W}\right)^2;$$

that is, for the same explosive, the resistance of cohesion of rock to rupture in blasting varies as the square of the line of resistance.

CHAPTER III.

FORCE DEVELOPED BY A BLAST.

26. *Conditions affecting the Force of an Explosion.*—In rock blasting, the forces P , P_1 , P_2 , P_3 , &c., in the formula $\frac{P}{S \times W} = \frac{P_1}{S_1 \times W_1} = \frac{P_2}{S_2 \times W_2}$, &c. $= K_1$, are obtained by the ignition or detonation of explosive compounds in closed chambers formed in the rock, whereby the explosive compound is converted from its solid or liquid state into gases in an inappreciably short space of time, this chemical conversion liberating heat and the gases in consequence highly expanding, and through such expansion exerting a great pressure on the rock. The force which is developed by blasting, therefore, depends on the following conditions :—

- (a) The absolute quantity of the gases produced.
- (b) The temperature of the gases.
- (c) The expansion of the gases due to the temperature resulting from the explosion.
- (d) The time occupied in obtaining the maximum expansion or pressure.
- (e) The size and form of the chamber.

- (f) The thermal conductivity of the surrounding medium.

27. *Of Different Action of Explosives.*—According to their properties explosives may be divided into two classes :—

- (a) Low, or slow and rending.
- (b) High, or quick and shattering.

The former are those in which the transformation into gas is comparatively slow, the explosive force being exerted by degrees as the gases are developed. The gases from such explosives being slowly evolved, the pressure upon the containing body cannot be much greater in any part than that which is exerted upon the part which yields. Gunpowder is the best type of such explosives.

The latter, on the contrary, are those in which the transformation of the explosive substance into gas occurs practically instantaneously. The full force of the enlarged volume is at once exerted in all directions, and upon every part of the containing body, because motion requires time ; and as no time is allowed for the less resistant part to yield by moving away before the full pressure of the fluid is developed, it follows that the whole force of the explosion is exerted upon its surroundings. Nitroglycerine and guncotton are the most prominent types of this class of explosives.

Between gunpowder and nitroglycerine as ex-

tremes the other explosives range according to their strength, and their applicability to rock blasting will depend on the nature of the rock, and also on whether the rock is to be shattered or broken in large blocks, and whether time is of very great importance in carrying out the work, as for instance in most railway tunnels.

28. *Maximum Pressures Developed by Explosives*.—The experiments of Sarrau, Vielle, Noble and Abel give the following as the approximate maximum pressures developed by mercury fulminate, nitroglycerine, guncotton and blasting-powder at their maximum densities :—

Mercury fulminate,	27,000	kg.	per square centimetre.
Nitroglycerine,	12,000	"	"
Guncotton,	10,000	"	"
Blasting-powder,	6,000	"	"

29. *The Useful Work of Explosives*, which consists partly in shattering the rock and partly in displacing the shattered masses, does not approach their theoretical on account of incomplete combustion, the escape of gas through the holes and fissures caused by the explosion at high pressure, and the thermal conductivity of the surrounding medium; moreover, energy is absorbed by the heating and cracking of the rock which is not displaced. According to von Rziha's experiments the useful effect is only 13·71 per cent., as given in the following table :—

Explosive.	Work in Metre-Kilogrammes.		Relative working value, Powder = 1.
	Theoretical.	Useful.	
Powder containing 62 per cent. saltpetre	242,335	33,224	1'0
Dynamite containing 75 per cent. nitroglycerine ..	548,250	75,165	2'2
Blasting-gelatine contain- ing 92 per cent. nitro- glycerine	766,913	105,144	3'2
Nitroglycerine	794,565	108,935	3'3

30. *The Power of an Explosive* cannot be calculated with precision from the quantity and temperature of the gases developed by the detonation or ignition of any explosive compound, owing to a want of knowledge of the state of dissociation of the gaseous products at the moment of explosion and during the period of cooling.

31. *Relative Force developed by an Explosive.*—We may obtain sufficiently accurate relative values of the maximum forces developed in different sizes and forms of chamber for blasting purposes by the aid of the two important laws of the statics of fluids given below if we assume that each unit of the same explosive compound will develop the same quantity of gases, and attain the same maximum pressure, under like conditions.

The two laws of the statics of fluids above referred to are—

- (a) That the pressure exerted by a fluid upon the different parts of the walls of the containing chamber are proportional to the areas of those parts.
- (b) That the pressures exerted by a fluid in any direction upon a surface is proportional to the projection of the surface at right angles to the given direction.

Since rock is invariably a very inelastic body, whose limit of elasticity is reached when it has undergone a very slight extension or change of form, it is evident that by the explosion of a charge in a chamber in the rock there will be no appreciable enlargement of the chamber before rupture takes place. Therefore, if M denotes the maximum pressure or shock per unit of surface in a chamber due to the explosion, and A and A_1 projections of two chambers at right angles to the direction of rupture, we can put for the absolute forces or pressures P and P_1 acting in the direction of rupture,

$$P = MA, \quad \text{and} \quad P_1 = MA_1,$$

whence

$$\frac{P_1}{P} = \frac{A_1}{A};$$

that is, the forces are directly proportional to the area of the projections; hence, for the use of the same explosive compound, the projection of chambers at right angles to their lines of resistance may be

taken to represent the relative forces which will be developed by the explosion of charges filling the chambers.

32. *Condition necessary for the Development of the Maximum Pressure of an Explosive.*—By experiments it has been proved that the maximum pressure or effect which any explosive substance can develop is that when detonating in a space entirely filled, viz. in a space equal to its own volume. Hence, to obtain the greatest disruptive effect the charge should entirely fill the chamber.

33. *Influence of the Form of Chamber and the Thermal Conductivity of the Rock on the Charge.*—When the blast has only the resistance of cohesion to overcome, as when the direction of rupture is downwards and there is no friction or hanging of the ruptured rock along the lines of fracture, the quantity of charge required will depend largely on the form of the chamber in which it is applied. For instance, a chamber whose cubical contents are $12 \times 12 \times 1$ will give as great pressure area to a charge, and overcome as great resistance in one direction, as another whose cubical contents are $12 \times 12 \times 2$, but the latter will take double the charge of the former to give the same rupturing effect. In the case given, it would therefore appear to be conducive to economy in the use of explosives to use a flattened form of chamber, or to attenuate the charge as much as possible. There is, however,

a limit to this, irrespective of the difficulty of boring such chambers, as a disproportionately large area of walls of the chamber to the quantity of explosive in the charge would cause a great loss of the force of the blast, owing to the thermal conductivity of the rock, which is proportional to the area of the walls of the chamber. Therefore the minimum width of the chamber should not be less than three-quarters of an inch if it be desired to obtain nearly the full effective pressure of the blast.

CHAPTER IV.

WEIGHT OF CHARGE REQUIRED TO EJECT ROCK AFTER RUPTURE.

34. *Ratio of Charge to Mass of Rock to be Moved.*
For any explosive compound of uniform strength, theory (see next article) and experience show that when a charge L will remove a mass M , under like conditions a charge $2L$ will move a mass $2M$, and a charge nL a mass nM , the masses being of the same specific gravity. If, therefore, for a given direction of movement the charges required for the volumes V and V_1 of a given kind of rock are L and L_1 we have the following relation of these quantities :—

$$L : L_1 :: V : V_1,$$

and consequently,

$$\frac{L_1}{L} = \frac{V_1}{V}.$$

35. *Ratio of Charge to Line of Resistance for similar Masses of Rock.*—The volumes V and V_1 , as they are similar in form, are proportional to the cube of any similar line within them, and, there-

fore, if W and W_1 are the lines of resistance corresponding to the volumes V and V_1 we have

$$\frac{V_1}{V} = \left(\frac{W_1}{W}\right)^3,$$

and substituting this value of $\frac{V_1}{V}$ in the formula $\frac{L_1}{L} = \frac{V_1}{V}$ we get

$$\frac{L_1}{L} = \left(\frac{W_1}{W}\right)^3.$$

The above formula agrees with that usually given in most works on rock blasting for estimating charges if we put the coefficient C_v for $\frac{L_1}{W_1^3}$, as we then obtain

$$L = C_v W^3.$$

36. *Theory of the Action and Force of a Blast after Rupture has taken place.*—The pressures, or tensions, and volumes of gas produced by the explosion of a charge in a chamber on the fractured mass abc (Figs. 10 and 11) by the force due to such pressures may be expressed by the law of Mariotte (or Boyle).

According to this law the density of one and the same quantity of gas is proportional to its tension, or pressure; or, since the space occupied by one and the same mass is inversely proportional to the density of the gas, the volumes of one and the same quantity of gas are inversely proportional to their tensions, or pressures.

Assuming, then, that the explosion of one unit of weight of any explosive having a constant chemical composition (when exploded under like conditions and neglecting the thermal conductivity of the chamber) to give a constant volume of gas at

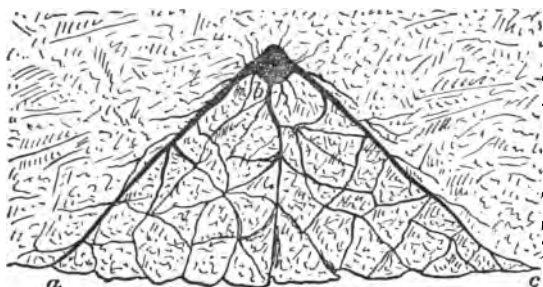


FIG. 10.

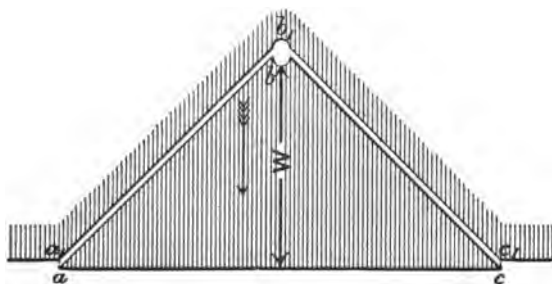


FIG. 11.

a certain tension, two such units to give two such volumes, three such units three such volumes, &c., it is evident, according to the above-mentioned law, that the quantity or volume of gas, or gases, produced by the explosion of a charge is directly proportional to the space occupied by the gas,

whereas the pressure on each unit of the walls of the containing chamber is in the inverse ratio of the volume of gas filling the chamber.

The space $V = a b c c_1 b_1 a_1$ (Fig. 11), formed by the movement of the fractured mass of rock $a b c$ in the direction of the line of resistance, is equal to the product of the surface $a c = F$ of the mass of rock $a b c$ and the distance $d = a a_1 = c c_1$ of such movement, and is as follows:—

For a line of resistance W , θ being a coefficient,

$$V = d F = \theta W \times \theta W \times d = \theta^2 \cdot d \cdot W^2.$$

For a line of resistance $W_1 = 2 W$,

$$V_1 = d F_1 = 2 \theta W \times 2 \theta W \times d = 4 \theta^2 \cdot d \cdot W^2.$$

For a line of resistance $W_n = n W$,

$$V_n = d F_n = n \theta W \times n \theta W \times d = n^2 \theta^2 \cdot d \cdot W^2.$$

Consequently,

$$\frac{V_n}{V} = \frac{F_n}{F} = \frac{n^2 \times \theta^2 \times d \times W^2}{\theta^2 \times d \times W^2} = n^2.$$

Or the space V and the surface F increase as the square of the line of resistance W , for the same movement d of the fractured mass $a b c$.

According to the statics of fluids the pressure exerted by a fluid in any direction is proportional to the projection of the surface at right angles to the given direction; hence the pressure exerted by the gas in the chamber in the direction of the line of resistance W is proportional to the surface $a c = F$, or the square of the line of resistance.

Since the volume of gas produced by a blast under the given conditions is proportional to the square of the line of resistance, its pressure is inversely as the square thereof, and for one and the same quantity of charge, supposing the pressure to be unity for a line of resistance = 1, we shall have the following relative pressures per unit of surface for any other lines of resistance.

Line of resistance.				Pressure of gas.
1	..	..	..	1
2	..	..	..	$\frac{1}{4}$
3	..	..	..	$\frac{1}{9}$
4	..	..	..	$\frac{1}{16}$
n	..	..	..	$\frac{1}{n^2}$

But the total pressure of the blast in the direction of the line of resistance is the product of the surface F and the pressure per unit of surface in the chamber, which may be expressed relatively as under:—

Line of resistance.				Relative pressure in direction of blast.
1	..	..	..	= 1
2	..	2 × 2	× $\frac{1}{4}$	= 1
3	..	3 × 3	× $\frac{1}{9}$	= 1
4	..	4 × 4	× $\frac{1}{16}$	= 1
n	..	n × n	× $\frac{1}{n^2}$	= 1

Consequently, the total pressure produced by the explosion of one and the same quantity of charge upon the mass of rock *abc* at any distance from its

bed may be taken as a constant quantity until the gases escape to the atmosphere, when the force of the blast is lost and the further projection of the mass is due to the velocity it has attained. The direction of movement of the ruptured mass of rock under the direct pressure of the blast corresponds with the line of resistance, and is indicated by the arrow in Fig. 11.

Since the total pressure developed by a blast upon a mass of rock at any point in its ejection from its bed is a constant quantity for one and the same quantity of charge, for a double quantity of charge at any given distance of the rock from its bed before the gases escape to the atmosphere the total pressure will also be constant, but double that for the single charge; and in like manner for a treble charge it will be trebled, and generally the force of the blast will be proportional to the quantity of charge.

On the contrary, the resistance of a ruptured mass of rock to a blast, when there is no friction or hanging of the same on the sides, is directly proportional to the product of its weight and the sine of the angle of the direction of the blast to the horizon. Therefore, calling the resistance R , the weight of the rock G , and the angle of the blast to the horizon α , we have

$$R = G \sin \alpha.$$

But since we can put $G = C W^3$

$$R = C W^3 \sin \alpha.$$

Therefore, for any other line of resistance R_1 we have

$$R_1 = C W_1^3 \sin \alpha,$$

and consequently

$$\frac{R_1}{R} = \left(\frac{W_1}{W}\right)^3$$

for any given direction of blast.

For R and R_1 , substituting the forces P and P_1 , required to overcome these resistances, we have

$$\frac{P_1}{P} = \left(\frac{W_1}{W}\right)^3.$$

But it has been demonstrated that the charges must be directly proportional to these forces, and denoting the charges which will develop the forces P and P_1 by L and L_1

$$\frac{P_1}{P} = \frac{L_1}{L}$$

and

$$\frac{L_1}{L} = \left(\frac{W_1}{W}\right)^3.$$

When, therefore, for a given direction of blast L has been found to be the proper charge for a line of resistance W , L_1 will be the proper charge for a line of resistance W_1 , conditionally that these charges are inserted in properly proportioned chambers to enable the gaseous pressure developed by

their explosion to overcome the cohesive resistance and weight, or inertia, of the rock, and that the masses of rock are similar in form.

37. *Sectional Area of Chamber required at Right Angles to the Line of Resistance.*—The ratio of the resistances R and R_1 to charges in chambers is

$$\frac{R_1}{R} = \frac{S_1 \times W_1 + \frac{G_1 \sin a_1}{K_1}}{S \times W + \frac{G \sin a}{K_1}}.$$

It is evident that the force of a blast must be made equal to the resistance of the rock, and that we must make

$$\frac{R_1}{R} = \frac{P_1}{P}.$$

Therefore, as $\frac{P_1}{P} = \frac{A_1}{A}$, A and A_1 being the sectional areas of charging chambers, we have

$$\frac{A_1}{A} = \frac{S_1 \times W_1 + \frac{G_1 \sin a_1}{K_1}}{S \times W + \frac{G \sin a}{K_1}}.$$

The value of $\frac{A}{S \times W + \frac{G \sin a}{K_1}}$ may be found

by trial blasts, and, therefore, if we put the coefficient C_a for this quantity we have, in general,

$$A = C_a (S \times W) + \frac{C_a G \sin a}{K_1}.$$

But as $\frac{C_a G \sin \alpha}{K_1} = 0$ when the direction of blast is horizontal, and it is always a comparatively small quantity, the sectional area of chamber may be calculated from the formula

$$A = C_a (S \times W)$$

in most cases.

The dimensions of the chamber depend also on the volume of charge required and the form of chamber.

38. *Chamber Coefficient.* — From the formula $A = C_a S W$ we have

$$\frac{A}{S} = C_a W = \theta.$$

The value θ may be called the chamber coefficient, as it depends solely on the form of chamber.

For any chamber whose section at right angles to the line of resistance is circular, if the diameter of the section is d , we have

$$A = .7854 d^2 \quad \text{and} \quad S = 3.1416 d,$$

whence,

$$\theta = \frac{.7854 d^2}{3.1416 d} = \frac{d}{4}$$

and

$$d = 4 \theta.$$

For any square section of chamber whose side is l ,

$$A = l^2 \quad \text{and} \quad S = 4 l,$$

hence

$$\theta = \frac{l^2}{4l} = \frac{l}{4}$$

and

$$l = 4\theta.$$

The coefficient for any other form of chamber may be found in a similar manner.

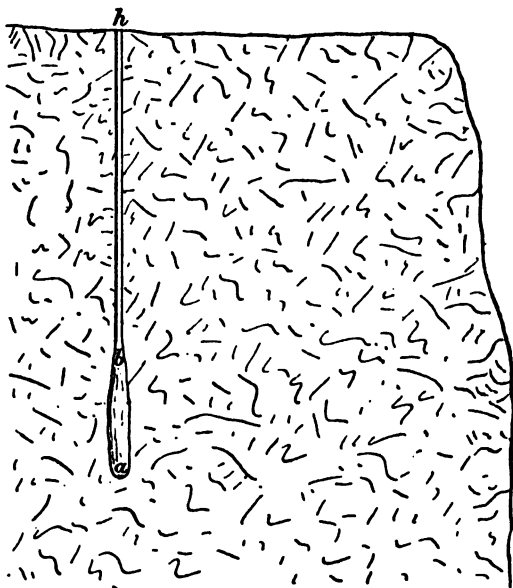


FIG. 12.

By the explosion of a charge in rock the sides of the chamber are corroded by the heat developed, but such corrosion does not affect the chamber coefficient appreciably. Hence, if the diameter of a borehole is too small to enable it to take sufficient

explosive to overcome the resistance of the rock to rupture the only effect of the blast will be to corrode the walls of the hole in immediate contact with the charge, so that the diameter of the hole will be enlarged, as illustrated in Fig. 12. A chamber *ab* is therefore produced, which may be further enlarged by repeating the process, until it will take sufficient explosive to rupture the rock. The best results are obtained with the strongest explosive and the use of only a little paper as tamping. If the hole is inclined below the horizon the size of the chamber may be ascertained by measuring the quantity of water required to fill the same. This operation is termed chambering, and if conducted by an experienced man will in some cases give good results.

CHAPTER V.

RELATIONS OF THE DIAMETERS OF BOREHOLES AND
SPHERICAL CHAMBERS TO LINES OF RESISTANCE.

39. *Boreholes and Chambers parallel to Free Face.*—For cylindrical and spherical chambers in rock, with the aid of the above enunciated principles, we can deduce very simple relations of the diameters to the lines of resistance, when the direction of rupture is horizontal.

Let l and l_1 be the lengths, and d and d_1 the diameters of two cylindrical chambers or boreholes in rock, which are placed at right angles to the line of resistance or parallel to the free face; then, if A and A_1 are the areas of projection of the chambers parallel to their axes,

$$A = l d \quad \text{and} \quad A_1 = l_1 d_1.$$

Therefore,
$$\frac{A_1}{A} = \frac{l_1 d_1}{l d}.$$

But, as before explained, $\frac{A_1}{A} = \frac{P_1}{P}$, P and P_1 being the forces developed by the charges filling the chambers before rupture takes place; and since $\frac{P_1}{P} = \frac{S_1 W_1}{S W}$, we have

$$\frac{A_1}{A} = \frac{S_1 W_1}{S W}.$$

Substituting for $\frac{A_1}{A}$ the value given above, we get

$$\frac{l_1 d_1}{l d} = \frac{S_1 W_1}{S W}.$$

When, however, the lengths of the chambers are a given multiple of the diameters,

$$\frac{l_1}{l} = \frac{S_1}{S} \quad \text{and consequently} \quad \frac{d_1}{d} = \frac{W_1}{W}.$$

Therefore, in blasting in the same kind of rock when the cohesive resistance is not affected by joints and fissures, the diameters of the boreholes should be directly proportioned to the lines of resistance.

In the case of spherical chambers, whose projections are A and A_1 , and diameters d and d_1 , we have

$$\frac{A_1}{A} = \frac{\frac{\pi}{4} d_1^2}{\frac{\pi}{4} d^2} = \left(\frac{d_1}{d}\right)^2,$$

and

$$\left(\frac{d_1}{d}\right)^2 = \frac{S_1 W_1}{S W}.$$

But $\frac{S_1}{S} = \frac{d_1}{d}$, and substituting $\frac{d_1}{d}$ for $\frac{S_1}{S}$ in the above equation, we get

$$\frac{d_1}{d} = \frac{W_1}{W}.$$

Consequently the same relations of the diameters to the lines of resistance subsist for spherical as for cylindrical chambers, viz. the diameters should be proportional to the lines of resistance.

By experiments in rock with a number of boreholes, varying in diameter from $\frac{3}{4}$ to $2\frac{1}{2}$ inches, we have obtained results quite in accordance with the above formula, thus proving its correctness and establishing the principles on which it is based.

With gelatine dynamite in a very homogeneous and strong granite our experiments gave the following results :—

No. of Expt.	Diameter of Borehole.	Depth of of Borehole.	Length of Charge.	Weight of Charge.	Line of Resistance.
	inches	ft. in.	inches	lbs.	ft. in.
1	$\frac{3}{4}$	3 2	9	·22	2 $4\frac{1}{2}$
2	1	4 2	12	·50	3 2
3	$1\frac{1}{4}$	5 3	15	1·00	4 0
4	$1\frac{1}{2}$	6 3	18	1·75	4 9
5	$1\frac{3}{4}$	7 3	21	2·80	5 6
6	2	8 4	24	4·20	6 4
7	$2\frac{1}{2}$	9 5	27	6·00	7 2

Manuel Eissler, in his valuable work on the modern high explosives, mentions that the ordinary mode of calculating charges is not exact, as it does not take into account the diameter of borehole and the whole face, and gives the following table of

lines of resistance resulting for boreholes of $1\frac{1}{4}$, $1\frac{1}{2}$ and $1\frac{3}{4}$ inches diameter, supposing No. 3 dynamite to be employed.

No. of Experiment.	DIAMETER OF BOREHOLES.		
	$1\frac{1}{4}$ in.	$1\frac{1}{2}$ in.	$1\frac{3}{4}$ in.
	LINE OF RESISTANCE.		
1	$3\frac{1}{2}$ feet	4 feet	5 feet
2	$3\frac{3}{4}$ "	5 "	6 "
3	5 "	6 "	7 "

The depths of the holes given are the following: for No. 1, equal to line of resistance; for No. 2, half as long again as the line of resistance; and for No. 3, double the line of resistance.

As will be observed, the lines of resistance in the above table are proportional to the diameter of the boreholes.

40. *Boreholes Angled to a Single Exposed Free Face.*—If a borehole be placed at a less angle than 90 degrees with the line of resistance, as in Fig. 13, when a single exposed face is to be attacked, we shall have the following relations for the forces P and P_1 , tending to produce rupture along the lines of resistance rn and qn perpendicular to the free face AB and borehole h respectively, if we put m for the length of charge in the borehole, d for the

diameter of borehole, a for the angle of the borehole with the line of resistance rn , W and W_1 for the lines of resistance along rn and qn respectively, K_1 for the modulus of shearing, and Q for the maxi-

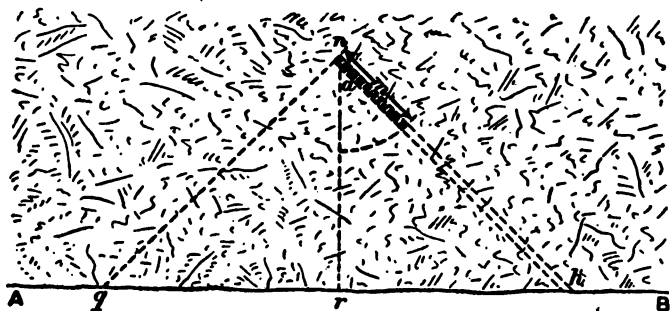


FIG. 13.

mum pressure or shock per unit of surface developed by the explosion of the charge, viz.

$$P = m d Q \sin a, \quad \text{and} \quad P_1 = m d Q.$$

For the resistances R and R_1 to the forces P and P_1 we may put

$$R = S W K_1 = 2 (m \sin a + d) W K_1,$$

and

$$R_1 = S_1 W_1 K_1 = 2 (m + d) W_1 K_1.$$

The line of least resistance is determined by whether the ratio of the force to the resistance is greater along rn than qn .

From the above equations,

$$\frac{P}{R} = \frac{m d \sin a}{2 W \times (m \sin a + d)} \times \frac{Q}{K_1}$$

and

$$\frac{P_1}{R_1} = \frac{m d}{2 W_1 \times (m + d)} \times \frac{Q}{K_1}.$$

But $W = W_1 \cos (90^\circ - a) = W_1 \sin a$, and

$$W_1 = \frac{W}{\sin a}.$$

Therefore, by substituting, we get

$$\frac{P_1}{R_1} = \frac{m d \sin a}{2 W (m + d)} \times \frac{Q}{K_1}.$$

It is clearly evident that $\frac{m d \sin a}{2 W (m \sin a + d)}$ is greater than $\frac{m d \sin a}{2 W (m + d)}$ when $\sin a < 1$, and,

consequently, $\frac{P}{R}$ is greater than $\frac{P_1}{R_1}$, from which we may conclude that there is a greater tendency to rupture along rn than qn ; and as it can be similarly demonstrated that there is less tendency to rupture along any other line between r and q , rn is the line of least resistance to the blast.

$\frac{P}{R} = \frac{m d \sin a}{2 W (m \sin a + d)} \times \frac{Q}{K_1}$ is a measure of the ratio of the force to the resistance when the borehole makes an angle a with the line of least resistance. For any smaller angle b , diameter of hole d_1 , length of charge m_1 , and line of least resistance W_1 , we can put

$$\frac{P_2}{R_2} = \frac{m_1 d_1 \sin b}{2 W_1 (m_1 \sin b + d_1)} \times \frac{Q}{K_1}.$$

Then, if we make $\frac{P}{R} = \frac{P_2}{R_2}$

$$\frac{m_1 d_1 \sin b}{2 W_1 (m_1 \sin b + d_1)} = \frac{m d \sin a}{2 W (m \sin a + d)}$$

and

$$\frac{W_1}{W} = \frac{(m m_1 d_1 \sin a \sin b) + (m_1 d d_1 \sin b)}{(m m_1 d \sin a \sin b) + (m d d_1 \sin a)}$$

or

$$\frac{W_1}{W} = \frac{(m m_1 d_1) + (m_1 d d_1 \operatorname{cosec} a)}{(m m_1 d) + (m d d_1 \operatorname{cosec} b)}.$$

This formula gives the relation of the lengths of charges, and diameters and angles of holes, for different lines of resistance W and W_1 in rock of the same cohesive strength.

If $m = n d$ and $m_1 = n d_1$

$$\frac{W_1}{W} = \frac{n d_1 + d_1 \operatorname{cosec} a}{n d + d \operatorname{cosec} b} = \frac{m_1 + d_1 \operatorname{cosec} a}{m + d \operatorname{cosec} b}.$$

If $W = W_1$ and the hole equal to the resistance W , whose diameter is d , is parallel to the free face, then $\operatorname{cosec} a = 1$, and we have

$$n d_1 + d_1 = n d + d \operatorname{cosec} b$$

$$(n + 1) d_1 = (n + \operatorname{cosec} b) d$$

and

$$d_1 = \left(\frac{n + \operatorname{cosec} b}{n + 1} \right) d.$$

If $n = 12$

$$d_1 = \left(\frac{12 + \operatorname{cosec} b}{13} \right) d.$$

When $\operatorname{cosec} a = 1$ and $n = 12$

$$\frac{W_1}{W} = \frac{13 d_1}{(12 + \operatorname{cosec} b) d}.$$

And if $d = d_1$

$$\frac{W_1}{W} = \frac{13}{12 + \operatorname{cosec} b}.$$

The formula $\frac{d_1}{d} = \frac{12 + \operatorname{cosec} b}{13}$ gives the ratio of the diameters d and d_1 of holes, parallel and angled to a free face respectively, for the same line of resistance, whereas for parallel and angled holes of the same diameter $\frac{W_1}{W} = \frac{13}{12 + \operatorname{cosec} b}$ gives the ratio of the lines of resistance.

From the above it is evident that a borehole will give the greatest efficiency when it is perpendicular to the line of resistance, and the least efficiency when the line of resistance coincides with the axis of borehole.

CHAPTER VI.

ON THE MAXIMUM DISTANCE APART THAT SIMILAR SHOTHOLES, WHEN IN LINE PARALLEL TO A FREE FACE, WILL DISLODGE THE WHOLE OF THE ROCK BETWEEN THEM WHEN FIRED SIMULTANEOUSLY, THE LINE OF RESISTANCE FOR EACH HOLE BEING THE SAME AS IF IT WERE TO BE FIRED INDEPENDENTLY, AND THE LINE OF RESISTANCE FOR TWO OR MORE SHOTHOLES SUPPORTING EACH OTHER.

41. *Maximum Distance which Shotholes should be Placed Apart in Strong and Homogeneous Rock.*—

If equal charges be placed in two boreholes $h h_1$ (Fig. 14) drilled parallel to the free face A B, so that the lines of resistance are equal, and fired simultaneously, the effect under certain conditions is much greater than if each were fired separately. For strong and homogeneous rock, when the charges have a length $= 12 d$, we get the following results.

- (a) When the distance between the charges $h h_1$ is greater than twice the line of resistance W, two independent craters of rock, $m h n$ and $n h_1 o$, will be dislodged.

- (b) When the distance $h h_1$ between the charges is equal to, or less than twice the line of resistance W , the masses of rock $m h n$ and $n h_1 o$ will be dislodged together with the intervening mass $n h h_1$.

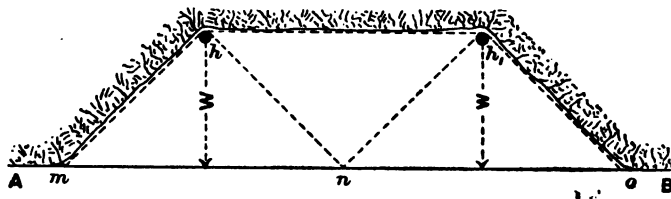


FIG. 14.

42. *Influence of the Cohesive Strength of Rock.*—

The maximum distance that the holes can be placed apart varies according to the cohesive strength of the rock.

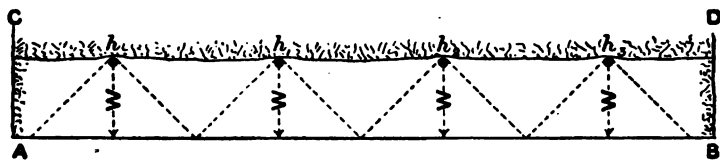


FIG. 15.

Suppose, for instance, the actual section of rock which the shotholes $h h_1 h_2 h_3$ (Fig. 15) would rupture if there were four lateral free faces, viz. A C B D (Fig. 15), and the free faces B D and E F shown in cross section (Fig. 16), when the line of resistance is of such length that the resistance to

shearing is exactly equal to the resistance to fracture of the cross section $h F$ by tension, assuming the rock to be perfectly inelastic, then, for the resistance to shearing for N shotholes we may put

$$N (S \times W \times K_1) = N S W K_1,$$

K_1 being the modulus of shearing; and if the height of section is equal to the distance between the shotholes for the resistance of the cross section to fracture by

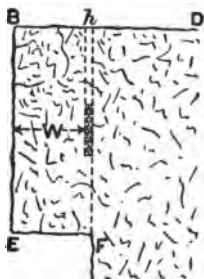


FIG. 16.

tension, we shall have

$$N (e W \times e W \times K) = N e^2 W^2 K$$

(K being the modulus of rupture by tension and $e W$ the distance between the shotholes) and therefore

$$N e^2 W^2 K = N S W K_1,$$

whence,
$$e = \sqrt{\frac{S}{W} \times \frac{K_1}{K}},$$

and
$$\frac{K_1}{K} = \frac{W}{S} e^2.$$

We have also (see Art. 37, p. 41)

$$A = S W C_a \quad \text{and} \quad A = S W_1 C_{a1},$$

$$\therefore \frac{W_1}{W} = \frac{C_a}{C_{a1}}.$$

Further, as the ratio of $\frac{K_1}{K} = C$ is a constant for different rocks,

$$e^2 = \frac{S}{W} \times C \quad \text{and} \quad e_1^2 = \frac{S}{W_1} \times C,$$

and consequently

$$\frac{W_1}{W} = \left(\frac{e}{e_1}\right)^2 \quad \text{and} \quad \left(\frac{e}{e_1}\right)^2 = \frac{C_a}{C_{a1}}.$$

In blasting rock we have obtained the following results, viz. with charges in 1 inch diameter boreholes having a length of twelve times the diameter of borehole :

For very strong rock,

$$e = 2.38 \quad \text{and} \quad \frac{S}{W} = \frac{26}{13} = 2.$$

For strong rock,

$$e = 2.00 \quad \text{and} \quad \frac{S}{W} = \frac{26}{18} = 1.44.$$

For moderately strong rock,

$$e = 1.50 \quad \text{and} \quad \frac{S}{W} = \frac{26}{34} = 0.765.$$

Therefore

$$\begin{aligned} \frac{K_1}{K} &= \frac{13}{26} \times (2.38^2) = 2.83 \\ &= \frac{18}{26} \times (2^2) = 2.77 \\ &= \frac{34}{26} \times (1.5^2) = 2.94 \end{aligned}$$

$$3 \overline{)8.54}$$

$$\text{Average value of } \frac{K_1}{K} = 2.84.$$

Assuming then $\frac{K_1}{K}$ to have a constant value of 2.84, we can find the value of e from any values of $\frac{W}{S}$, or *vice versa*. For instance, putting $e = 1$ and $S = 26$ inches for weak rock, we have

$\frac{W}{26} = 2.84$ and $W = 73.84$ inches for a 1 inch diameter borehole.

It is, however, important to note that, in consequence of the low cohesive strength of the rock, the chief factor in determining the charge in this case will be the force required to eject the rock after rupture.

From the above we have the following rule:—

For very strong rock, boreholes, having a length of charge = 12 d , should be placed a distance 2 W to 2.38 W ; for strong rock, a distance $1\frac{1}{2}$ W to 2 W ; for moderately strong rock, W to $1\frac{1}{2}$ W ; and for weak rock, a distance W apart.

On the other hand, for the same rock it must be noted, that the value of e depends on the length of charge, as we have

$$e = \sqrt{2.84 \frac{S}{W}} \quad \text{and} \quad e_1 = \sqrt{2.84 \frac{S_1}{W}}.$$

Therefore

$$\frac{2.84 \frac{S_1}{W}}{2.84 \frac{S}{W}} = \left(\frac{e_1}{e}\right)^2 \quad \text{and} \quad \frac{S_1}{S} = \left(\frac{e_1}{e}\right)^2.$$

Consequently,

$$S_1 = \left(\frac{e_1}{e}\right)^2 S.$$

A 1-inch shothole gives $e = 1\frac{1}{2}$ and $S = 26$ for moderately strong rock when the length of charge = 12 d .

Hence, to obtain $e = 2$ we must have

$$S = \left(\frac{2}{1\frac{1}{2}}\right)^2 \times 26 = 46.22 \text{ inches.}$$

For $S = 46.22$ inches, the length of charge will be $\frac{46.22 \text{ inches} - 2}{2} = 22.11$ inches.

Simultaneous firing may, therefore, for hard rock

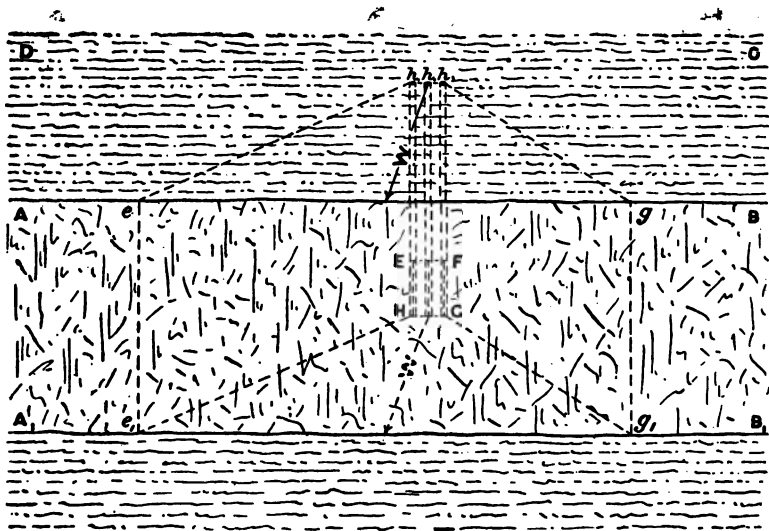


FIG. 17.

be productive of a greatly increased useful effect compared with the firing of the same charges consecutively, there being a saving of about 20 per cent. in the cost of blasting under certain conditions. It is, moreover, a valuable means of concentrating the forces of several charges to overcome a greater

line of resistance than each is capable of when fired simultaneously.

43. *Line of Resistance for the combined Shearing Force of any Number of Similar Shotholes, equidistant from each other, in Line Parallel to a Free Face.*—In the case of a long line of free face (Figs. 17 and 18), a number of similar shotholes in line parallel thereto and equidistant from each other, when placed a certain

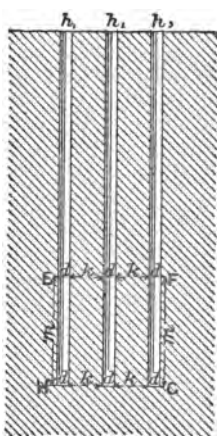


FIG. 18.

distance k apart will overcome a line of resistance $W_n = q W$, W being the line of resistance corresponding to a single charge, if the charges be fired simultaneously. The value of q may be found in the following manner.

For one shothole,

$$W = \frac{A}{C_a S} = \frac{A}{C_a (2m + 2d)},$$

m being length of charge and d diameter of borehole, therefore we have the following values for

S when all the shotholes are of the same diameter and placed near each other in line parallel to the free face,

For two shotholes $h h_1$ (Fig. 18),

$$S = E F G H = 2m + 4d + 2k.$$

For three shotholes $h h_1 h_2$ (Fig. 18),

$$S = E F G H \times 2m + 6d + 4k.$$

And for N shotholes

$$S = 2m + 2Nd + (2N - 2)k.$$

Hence, for two shotholes,

$$W_1 = \frac{2A}{C_a(2m + 4d + 2k)};$$

For three shotholes,

$$W_2 = \frac{3A}{C_a(2m + 6d + 4k)};$$

For four shotholes,

$$W_3 = \frac{4A}{C_a(2m + 8d + 6k)};$$

For N shotholes,

$$W_n = \frac{NA}{C_a(2m + 2Nd + (2N - 2)k)}.$$

If $W_n = qW$ we have $\frac{A}{C_a W_n} = \frac{S}{q}.$

Consequently

$$\frac{N}{2m + 2Nd + (2N - 2)k} = \frac{q}{S}$$

$$NS = N(2qd + 2qk) = 2qm - 2qk.$$

$$N = \frac{2qm - 2qk}{S - (2qd + 2qk)},$$

$$N = \frac{2(m - k)}{\frac{S}{q} - 2(d + k)}$$

and

$$q = \frac{NS}{2((m + Nd) + k(N - 1))}.$$

When q is less than unity, the combined shearing force is not so great as the shearing force of each shothole acting independently, in which case the line of resistance will be limited by the latter.

44. *Economy of Firing several similar Charges close together in Line Parallel to a Free Face.*—Great economy may be obtained in blasting very hard rock which is without well defined joints, when there is a sufficient length of free face, by the use of a number N of similar shotholes placed close to each other in line parallel to the free face, and firing them simultaneously. Such economy is due to the greater line of resistance that may be blasted by their combined action than if each were fired singly, as the quantity of rock blasted increases as the cube of the line of resistance.

$$\text{The value of } q = \frac{NS}{2((m + Nd) + (N - 1)k)}$$

(see Art. 43), for similar charges applied in boreholes of 1 inch diameter which are placed 3 inches apart, in line parallel to a free face, length of charge being 12 inches, is as follows :

- (a) For $N = 1$ $q = 1$
- (b) „ $N = 2$ $q = 1\frac{9}{17}$
- (c) „ $N = 3$ $q = 1\frac{6}{7}$
- (d) „ $N = 4$ $q = 2\frac{2}{5}$

That is, the line of resistance increases as q with the number of charges.

On the contrary, the coefficient C_v in the formula

$$L = C_v W^3$$

decreases with the number of charges as the quantity of rock blasted increases in a greater ratio.

And as we can put

$$L_1 = C_{v1} W_1^3$$

for the quantity of the charge in N shotholes, we have

$$N C_v W^3 = C_{v1} W_1^3$$

and consequently,

$$C_{v1} = \frac{N C_v}{q^3}.$$

By substituting the value of N and q , given above in this formula, we get

$$(a) \quad C_{v1} = C_v.$$

$$(b) \quad C_{v2} = \frac{2 C_v}{\left(\frac{9}{117}\right)^3} = .56 C_v.$$

$$(c) \quad C_{v3} = \frac{3 C_v}{\left(\frac{6}{17}\right)^3} = .46 C_v.$$

$$(d) \quad C_{v4} = \frac{4 C_v}{\left(\frac{2}{25}\right)^3} = .29 C_v.$$

C_v , as found for a single shothole 1 inch in diameter, namely, for a quantity of rock W^3 , is, consequently, reduced to .29 C_v for a quantity of rock $\left(2\frac{2}{25} W\right)^3 = W_1^3$, blasted by the combined action of four shotholes of the same diameter and containing similar charges. The limiting value of C_v is that required for the ejection of the rock.

CHAPTER VII.

QUANTITY OF ROCK WHICH WILL BE LOOSENED
UNDER THE USUAL CONDITIONS OF BLASTING
OPERATIONS, WHEN THERE ARE NO WELL DE-
FINED JOINTS OR FISSURES.

45. *The usual Method of Exavating Rock by Blasting*, when there are no well defined joints, is in steps or benches with straight free faces at right angles to each other, as represented in Figs. 19, 20, 21, and, except when the rock is cut up into very large blocks by joints, in which case the line of resistance is so regulated as to enable the blasts to break right up to the joints, it invariably gives the best results.

46. *Form of Craters*.—Fig. 19 shows the crater $efg g_1 f_1 e_1$, which will be formed by the blast of a single shothole in a step of rock when there are only two free faces AB_1 and AC ; Fig. 20, the crater $efC C_1 f_1 e_1$, which will be formed when there are three free faces AB_1 , AC and BC_1 ; Fig. 21, the mass of rock bounded by the sides AB_1 , AC , AD_1 , BC_1 , DC_1 , and $A_1 C_1$, which will be blasted when there are four free faces AB_1 , AC , AD_1

and BC_1 ; and Fig. 22, the crater $efghh_1g_1f_1e_1$ which will be formed when there are only two free faces as in Fig. 19, and several similar shotholes are fired in line parallel to the free face AB_1 simultaneously.

47. *Angle of Lines of Rupture.*—If the rock is a homogeneous mass, and there are only two free

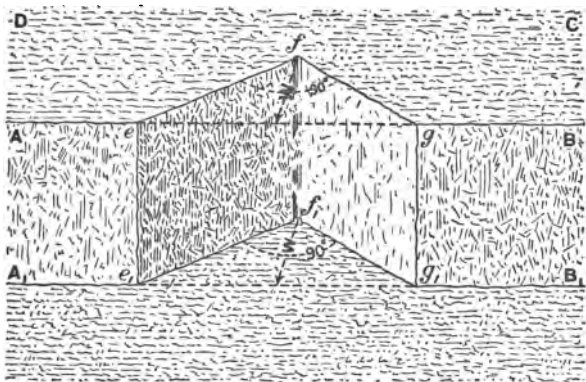


FIG. 19.

faces as in Fig. 19, the angle of the main lines of rupture efg or $e_1f_1g_1$ may be considered, for all practical purposes, to form a right angle or 90° with each other, or each to have an angle of 45° with the free face A_1B_1 , and in the case of there being other free faces as AD_1 and BC_1 (Fig. 21), the main lines of rupture for each may also make as great an angle as 90° if the face is of sufficient extent.

48. *Volume V of Rock Dislodged when there are Two Free Faces at Right Angles to each other.*—In accordance with the above, a shothole having two free faces will dislodge the volume of rock $efg g_1 f_1 e_1$ (Fig. 19).

$$V = W^3 + \frac{m}{2} W^2.$$

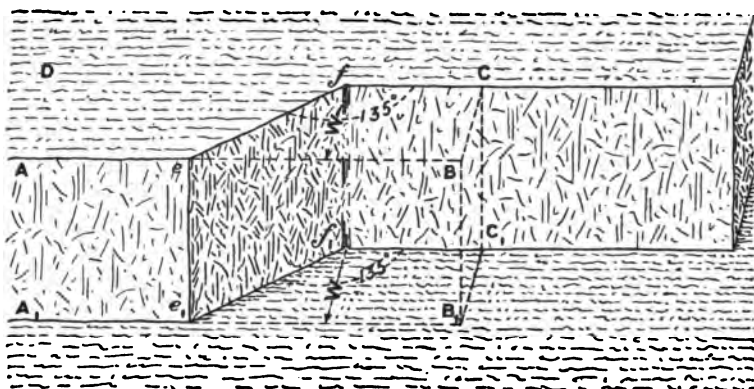


FIG. 20.

49. *Volume V of Rock Dislodged when there are Three or Four Free Faces at Right Angles to each other.*—If there are three free faces, the mass of rock dislodged will have a volume $efC C_1 f_1 e_1 B_1 B$ (Fig. 20), and in case of four free faces the volume $A D C C_1 D_1 A_1 B_1$ (Fig. 22).

For three free faces $V = \frac{3}{2} W^3 + \frac{3}{4} m W^2$.

„ four „ $V = 2 W^3 + m W^2$.

50. *Volume V of Rock Dislodged by any Number of Similar Shotholes in a Step of Rock.*—In the case of several similar shotholes in line parallel to the face of rock A B₁ (Fig. 22), and the charges fired simultaneously, the mass of rock loosened will have a volume $e f g h h_1 g_1 f_1 e_1$ (Fig. 22).

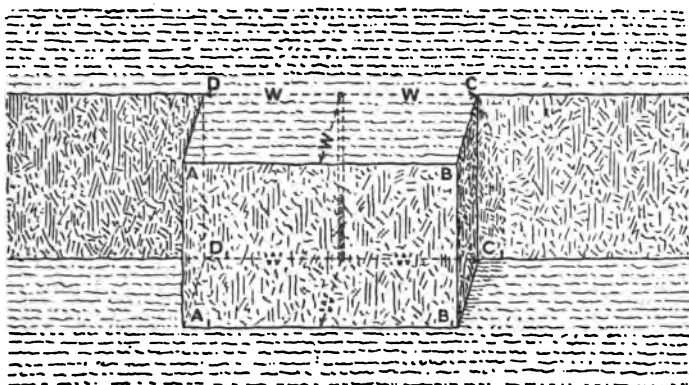


FIG. 21.

Hence

$$V = \left\{ (n - 1) + \frac{1}{2} \right\} e W^3 + \left((n - 1) \frac{m}{2} + \frac{m}{4} \right) e W^2.$$

Therefore, if $e = 2$,

For two shotholes (fired simultaneously),

$$V = 3 W^3 + \frac{3}{2} m W^2.$$

For three shotholes (fired simultaneously),

$$V = 5 W^3 + \frac{5}{2} m W^2.$$

For four shotholes (fired simultaneously),

$$V = 7 W^3 + \frac{7}{2} m W^2.$$

Consequently, in blasting with similar shotholes, when there are no joints or fissures to be considered,

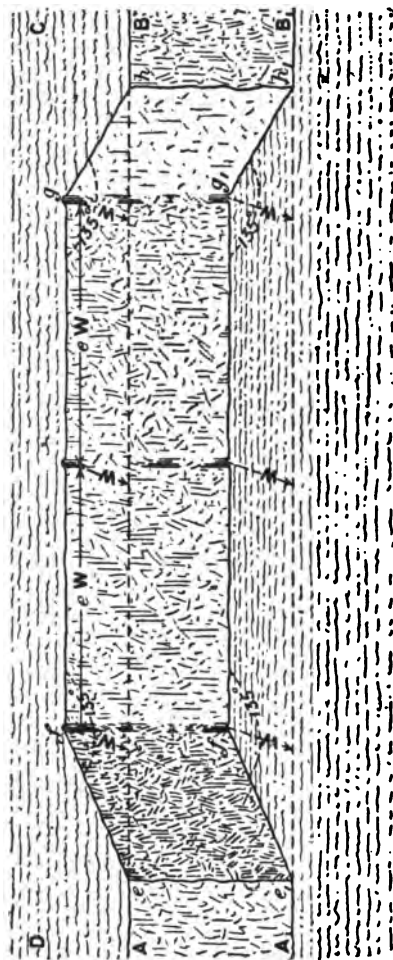


FIG. 22.

two holes fired simultaneously with two free faces will dislodge the same volume of rock as two such

holes fired singly each with three free faces; three shotholes fired simultaneously with two free faces, the same volume of rock as two such holes fired singly each with three faces, and one other with four free faces; and four shotholes fired simultaneously with two free faces, the same volume of rock as two such holes fired singly each with three free faces, and two others fired singly each with four free faces.

51. *Volume of Rock blasted by a Concentrated Charge.*—According to our observations, the approximate volumes of rock which will be blasted in the case of a concentrated charge, and when the free faces are of sufficient extent to allow of full scope of action to the blast, are as follows:

For one free face	$1\frac{1}{3} W^3$.
„ two free faces at right angles to each other	$1\frac{2}{3} W^3$.
„ three ditto ditto	$2\frac{1}{3} W^3$.
„ four ditto ditto	$3 W^3$.
„ five ditto ditto	$4 W^3$.
„ six ditto ditto or a cubical block of stone	$8 W^3$.

The relative economy under the different conditions of free face and firing of the charges is evidently proportional to the volumes of rock blasted.

52. *Simultaneous and Consecutive Firing.*—It is evident from the above that the simultaneous firing of a number of shots will offer important advantages. This is especially the case, as before explained, when a number of shotholes are properly combined for the blasting of a long and straight wall of rock as indicated in Fig. 22, or for “unkeying” a single exposed surface of rock as by the four central shots Nos. 1 to 4 (Fig. 34). Cases, however, occur in which it is necessary to determine the order of the explosions to obtain the best effect, as for instance, for the enlarging shots numbered 5 to 24 (Fig. 34).

CHAPTER VIII.

THE LENGTH OF CHARGES IN BOREHOLES FOR RUPTURE BY SHEARING.

53. *Charges for Shearing.*—The best or most economical length for charges in boreholes may be deduced from the formula $W = \frac{A}{C_a S}$ in the following manner :

As $A = m d$, and $S = 2 (m + d)$,

$$W = \frac{m d}{2 C_a (m + d)}.$$

Therefore, when

$$m = d \quad W = \frac{1}{2} \frac{d}{2 C_a}$$

$$m = 2 d \quad W = \frac{2}{3} \frac{d}{2 C_a}$$

$$m = 3 d \quad W = \frac{3}{4} \frac{d}{2 C_a}$$

$$m = 4 d \quad W = \frac{4}{5} \frac{d}{2 C_a}$$

$$m = 5 d \quad W = \frac{5}{6} \frac{d}{2 C_a}$$

$$m = 6 d \quad W = \frac{6}{7} \frac{d}{2 C_a}$$

$$m = 7 d \quad W = \frac{7}{8} \frac{d}{2 C_a}$$

$$m = 8 d \quad W = \frac{8}{9} \frac{d}{2 C_a}$$

$$m = 9 d \quad W = \frac{9}{10} \frac{d}{2 C_a}$$

$$m = 10 d \quad W = \frac{10}{11} \frac{d}{2 C_a}$$

$$m = 11 d \quad W = \frac{11}{12} \frac{d}{2 C_a}$$

$$m = 12 d \quad W = \frac{12}{13} \frac{d}{2 C_a}$$

On the contrary, for the coefficient $C_v = \frac{L}{W^3}$, L being the weight of the charge, and W the line of resistance, we have, if $E m$ represents the weight of charge L ,

$$C_v = \frac{E m}{W^3}.$$

Therefore, when

$$m = d \quad C_v = \frac{E d}{\left(\frac{1}{2} \frac{d}{2 C_a}\right)^3} = 8 \frac{(E C_a^3)}{d^2}$$

$$m = 2d \quad C_v = \frac{E \, 2d}{\left(\frac{2}{3} \frac{d}{2C_a}\right)^3} = 6\frac{3}{4} \frac{(8E C_a^3)}{d^2}$$

$$m = 3d \quad C_v = \frac{E \, 3d}{\left(\frac{3}{4} \frac{d}{2C_a}\right)^3} = 7\frac{1}{9} \frac{(8E C_a^3)}{d^2}$$

$$m = 4d \quad C_v = \frac{E \, 4d}{\left(\frac{4}{5} \frac{d}{2C_a}\right)^3} = 7\frac{13}{8} \frac{(8E C_a^3)}{d^2}$$

$$m = 5d \quad C_v = \frac{E \, 5d}{\left(\frac{5}{6} \frac{d}{2C_a}\right)^3} = 8\frac{16}{25} \frac{(8E C_a^3)}{d^2}$$

$$m = 6d \quad C_v = \frac{E \, 6d}{\left(\frac{6}{7} \frac{d}{2C_a}\right)^3} = 9\frac{19}{36} \frac{(8E C_a^3)}{d^2}$$

$$m = 7d \quad C_v = \frac{E \, 7d}{\left(\frac{7}{8} \frac{d}{2C_a}\right)^3} = 10\frac{22}{49} \frac{(8E C_a^3)}{d^2}$$

$$m = 8d \quad C_v = \frac{E \, 8d}{\left(\frac{8}{9} \frac{d}{2C_a}\right)^3} = 11\frac{25}{44} \frac{(8E C_a^3)}{d^2}$$

$$m = 9d \quad C_v = \frac{E \, 9d}{\left(\frac{9}{10} \frac{d}{2C_a}\right)^3} = 12\frac{28}{81} \frac{(8E C_a^3)}{d^2}$$

$$m = 10d \quad C_v = \frac{E \, 10d}{\left(\frac{10}{11} \frac{d}{2C_a}\right)^3} = 13\frac{31}{100} \frac{(8E C_a^3)}{d^2}$$

$$m = 11 d \quad C_v = \frac{E \ 11 d}{\left(\frac{11}{12} \frac{d}{2 C_a}\right)^3} = 14 \frac{34}{121} \frac{(8 E C_a^3)}{d^2}$$

$$m = 12 d \quad C_v = \frac{E \ 12 d}{\left(\frac{12}{13} \frac{d}{2 C_a}\right)^3} = 15 \frac{37}{144} \frac{(8 E C_a^3)}{d^2}$$

From the values of W given above, it is evident that if the length of the charge m be infinitely increased beyond $12 d$, W will only be increased $\frac{1}{12}$, or beyond $8 d$ no more than $\frac{1}{8}$, and as C_v increases as shown with the length of charge, as a general rule, owing to the influence of the periphery of the charging chamber on the blast as explained below, the limits of the length of charge should vary between $8 d$ and $12 d$ according to the degree of economy required in the consumption of explosive.

54. *Influence of Form of Chamber on Shearing Force of Charge.* — According to the formula

$W = \frac{A}{C_a S}$ it appears that an elongated charge, as

in a borehole, is not a favourable form for obtaining the least resistance to a blast for a given line

of resistance, for, as $\frac{A}{S}$ represents the influence of

the form of chamber on the shearing force of the charge, the resistance will decrease as the sectional area, or projection of the chamber at right angles

to the direction of the blast, approaches a square, and is a minimum when such projection is a circle. This, however, only obtains in case there is only one free face, for if there are lateral free faces it is advantageous to have an elongated charge to insure the whole mass of rock being carried away to such free faces, as with a relatively high value of $\frac{A}{S}$ the blast would produce a conical cavity in the centre of the mass and not carry away the rock to the lateral free faces.

55. *The Length of Charge in Boreholes should be a Constant Multiple of the Diameter for Shearing.*—When the lengths of charges used in boreholes are made a constant multiple of their diameters, as, for instance, $n d$, we can put for the weight of charge L for a diameter of borehole d ,

$$L = .7854 d^2 n d E = .7854 E n d^3,$$

E representing the weight of a cubic inch of explosive, and for a diameter of borehole d_1

$$L_1 = .7854 E n d_1^3.$$

Therefore,

$$\frac{L_1}{L} = \left(\frac{d_1}{d}\right)^3,$$

But as $\frac{d_1}{d} = \frac{W_1}{W},$

$$\frac{L_1}{L} = \left(\frac{W_1}{W}\right)^3,$$

which evidently agrees with the formula

$$L = C_v W^3 \text{ as } C_v = \frac{L_1}{W_1^3}.$$

Hence, if we have found that a length of charge $n d$ in a borehole whose diameter is d , will give the proper charge for the line of resistance corresponding to this diameter of borehole and the weight of rock to be ejected, then a length of charge $n d_1$ will give the proper charge for the line of resistance corresponding to any diameter of borehole d_1 in the same rock.

CHAPTER IX.

THE BEST POSITION FOR A CHAMBER OR CHARGE WHEN
THERE ARE TWO OR MORE FREE FACES AT RIGHT
ANGLES TO EACH OTHER.

56. *Principle on which the Best Position for a Chamber may be determined.*—To obtain the best effect with a blast in rock there must be equilibrium of resistance on all sides of the line of resistance to the action of the charge; hence the position of the chamber should be determined on this principle.

57. *Rule for determining Distance of Chamber from Free Faces.*—As before explained (Art. 42), when two or more similar charges are situated a distance eW apart ($e = 2$ for strong rock, $1\frac{1}{2}$ for moderately strong rock, and 1 for weak rock) in homogeneous rock, parallel to a straight free face, and fired simultaneously, the whole of the intervening rock is dislodged; but when the distance between the holes exceeds eW each charge will blast a distinct crater. We may therefore conclude that the limiting distance of action for each charge is midway between the holes, or a distance $\frac{eW}{2}$.

Therefore, as the force of a blast in a borehole chamber is equally great on any side of the same except the ends, and such force will overcome the same resistance of rock on any side having a free face, the distance of any lateral free face from the side of borehole should be equal to the line of resistance; and, on the contrary, for a free face at right angles to the axis of borehole the distance of same from the centre of the charge should be $\frac{eW}{2}$, as the pressure of the blast on the end of the borehole is comparatively small, and could not produce rupture acting independently of the lateral pressure in the hole.

From the above considerations we have deduced the following rule for determining the proper position for a borehole chamber, viz. :—

The distance from the centre of a charge to any lateral free face, measured perpendicularly to the axis of the borehole, should be the same as the line of resistance, and to any end free face, measured in line with the axis of borehole, a length $\frac{eW}{2}$.

When $e = 2$ the distance from the centre of charge to any free face should be the same as the line of resistance, which may be adopted in practice as sufficiently accurate under most conditions.

Therefore, for two free faces at right angles to each other the proper position for a borehole charge

is that illustrated in Fig. 23, in plan, and Fig. 24, in section, in which AB and CE represent the free faces, h the borehole, D the depth of borehole, m

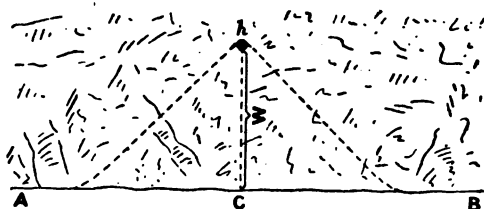


FIG. 23.

the length of charge, and T the tamping, or length of borehole above the charge.

Accordingly,

$$D = m + T.$$

$$\text{And as } T = W - \frac{m}{2}$$

$$D = \frac{m}{2} + W.$$

For three free faces the position of the charge should be that indicated in Fig. 25 in plan, and Fig. 26, in section.

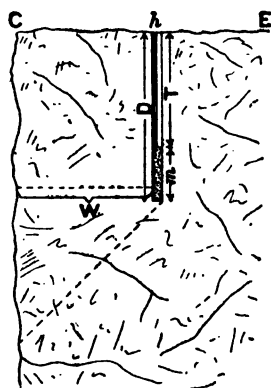


FIG. 24.

58. *Main Lines of Rupture.*—For rock of homogeneous composition and uniform texture the main lines of rupture, ha , he and hB (Fig. 25), would

reach the surface as indicated by the dotted lines, that is, they make an angle of 180° between the

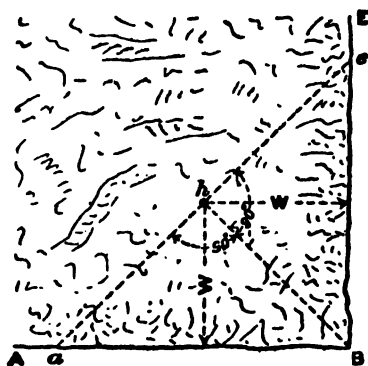


FIG. 25.

two lateral free faces, or an angle of 90° for each free face.

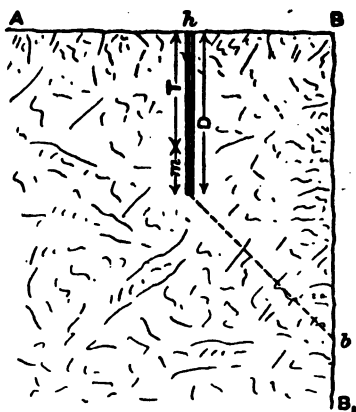


FIG. 26.

Owing to the want of homogeneity in rock, and to the existence of joints and fissures, the outer line

of rupture will not, in practice, run so regularly as indicated by the dotted lines. In case of rupture by shearing the line of rupture is a slightly convex curve, as shown in Fig. 1.

59. *Irregular Faces of Rock.*—A circumstance which will influence the position of the chamber, sometimes in a very important degree, and which must be taken into account in estimating the line of resistance, is the irregularity of the faces of the rock, which, instead of forming unbroken planes parallel to the borehole, are broken up more or less by projecting bosses and deep depressions. Experience and good judgment, combined with a knowledge of the principles of blasting, must guide the blaster in this case.

CHAPTER X.

BOREHOLE CHARGES.

60. *Formulae for Weight of Borehole Charges.*— Calling d the diameter of borehole, $n d$ the length of charge, g the specific gravity of the explosive, U the cubical contents of charge, and L the weight of charge in lbs., we have

$$U = .7854 d^2 \times n d$$

$$U = .7854 n d^3.$$

The weight of one cubic inch of any explosive in lbs. is $.036 g$, and consequently, when d is expressed in inches,

$$L = .7854 n d^3 \times .036 g$$

$$L = .0283 n g d^3.$$

When $n = 12$, and $g = 1.6$ as for dynamite,

$$L = .0283 \times 1.6 \times 12 d^3$$

$$L = .5434 d^3.$$

The weight of charge is also given by the formula

$$L = C_v W^3.$$

But as the charge must be applied in a chamber giving sufficient pressure area to the blast, at right angles to the line of resistance, to overcome the cohesive strength of the rock, it is often more useful to have it expressed in terms of C_a and W , by substituting the value of C_a in terms of C_v in the above formula. The value of C_a in terms of C_v may be found in the following manner:

$$\text{Since } L = C_v W^3 = .3396 g d^3.$$

$$\left(\frac{d}{W}\right)^3 = \frac{C_v}{.3396 g}.$$

$$\frac{d}{W} = \sqrt[3]{\frac{C_v}{.3396 g}}.$$

But for a borehole chamber whose projection is $A = C_a S W$, we have $A = n d^2$, and $S = (n + 1) 2 d$.

$$\text{Therefore } C_a = \frac{n d}{2 (n + 1) W},$$

and

$$\frac{d}{W} = \left(\frac{2n + 2}{n}\right) C_a.$$

From the above values of $\frac{d}{W}$ we have

$$\left(\frac{2n + 2}{n}\right) C_a = \sqrt[3]{\frac{C_v}{.3396 g}}$$

and

$$C_a = \left(\frac{n}{2n + 2}\right) \sqrt[3]{\frac{C_v}{.3396 g}}.$$

When $n = 12$

$$C_a = \frac{12}{26} \sqrt{\frac{C_v}{.3396 g}} = \frac{6}{13} \sqrt[3]{\frac{C_v}{.3396 g}}$$

and

$$C_v = 3.454 g C_a^3.$$

When W is expressed in feet

$$C_v = 5969 g C_a^3.$$

Substituting these values of C_v in the formula $L = C_v W^3$, we have, when W is expressed in inches,

$$L = 3.454 g C_a^3 \cdot W^3;$$

when W is expressed in feet

$$L = 5969 g C_a^3 \cdot W^3.$$

Suppose, for example, for a borehole in very strong rock, that $C_a = .02$, then C_v must be

$$3.454 g \times .02^3 = .00002763 g$$

to enable the blast to produce rupture.

If W in the formula $L = C_v W^3$ be taken in feet, and in the formula $A = C_a S W$ in inches,

$$C_v = .00002763 g \times 1728 = .048 g.$$

CHAPTER XI.

THE INFLUENCE OF FISSURES, JOINT AND BEDDING
PLANES IN DETERMINING THE CHARGE.

61. *Favourable Conditions for Quarrying Operations.*—A consideration of great importance is the existence of fissures, joint planes and bedding planes, also lines of statification. It often happens that a bed of rock is cut up by such planes into detached blocks of greater or less dimensions, which must be considered as more or less unsupported faces to determine the proper position for a charge, and the length of the line of resistance. In some quarries joints traverse rocks in straight and well determined lines, and are slightly open, thus affording to the quarryman the greatest aid in the extraction of blocks of stone. When a sufficient number of joints cross each other the whole mass of rock is split into symmetrical blocks, and offers the best possible conditions for quarrying operations.

62. *Rupture without Shearing. The Resistance to Rupture of any Section of Rock limited by Joints or Free Faces.*—In the case of joints and free faces, as in blasting a mass of rock $eflkfglm$, Fig. 27,

which is bounded by the free faces AB_1 and AD , the vertical joints $efgh$ and $klmn$, and the bedding joint $e_1gm k_1$, if the joints have little or no cohesion along their surfaces, and they are parallel or diverge towards the front face AB_1 , the cohesive resistance

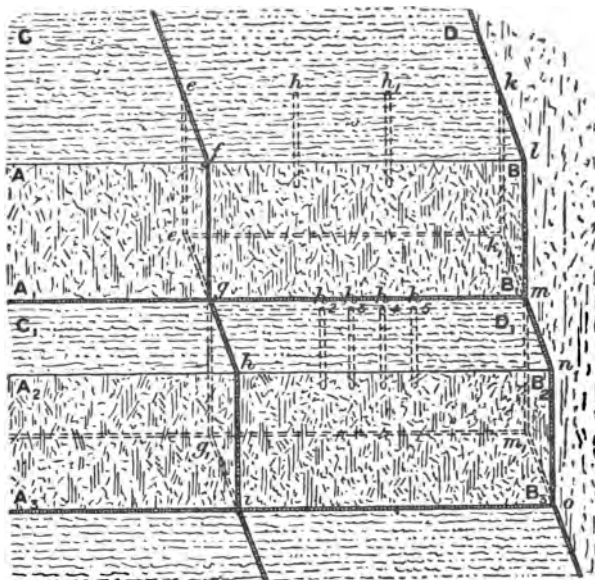


FIG. 27.

of the rock to be overcome by the shotholes $h h_1$ will be proportional to the smallest section of the mass through the shotholes, which should be bored between the joints and parallel to the front face. Suppose F and F_1 to be any two such sections of similar rock, varying according to the distance

between the joints, and that the same could be ruptured by shotholes having charges of the same kind of explosive, and whose respective charging chambers have projections A and A_1 parallel to the front face AB ; then for any given line of resistance W it is evident that we should have the following relations of the quantities F and F_1 , A and A_1 , and S and S_1 , viz.

$$\frac{F_1}{F} = \frac{A_1}{A} = \frac{S_1}{S}.$$

On the contrary, for rocks of different cohesive strength, and shotholes of the same diameter, the lines of resistance should be proportional to the cohesive strength of the rocks, as we should have

$$F = e^2 W^2, \quad \text{and} \quad F_1 = e_1^2 W_1^2$$

and

$$\frac{F_1}{F} = \left(\frac{e_1 W_1}{e W} \right)^2.$$

But we can put F = the section that would require the same force to rupture it as the section F_1 in a different rock, under which conditions $A = C_a S W$ equals $A = C_{a1} S W_1$, and therefore

$$\frac{C_a}{C_{a1}} = \frac{W_1}{W}.$$

Consequently,

$$\frac{F_1}{F} = \left(\frac{e_1}{e} \right)^2 \left(\frac{C_a}{C_{a1}} \right)^2,$$

and as $\left(\frac{e_1}{e} \right)^2 = \frac{C_{a1}}{C_a}$ (see Art. 42, page 54)

$$\frac{F_1}{F} = \frac{C_a}{C_{a1}}$$

and

$$F_1 = \frac{C_a}{C_{a1}} F.$$

For very strong rock (see Table I.), when $C_a = .032$, we find $e = 2.27$, and for a 1-inch diameter shothole charged with dynamite, $A = 12$ square inches, and $W = 14.37$ inches.

Therefore,

$$\begin{aligned} F = e^2 W^2 &= (2.27)^2 \times (14.37)^2 = 1064 \text{ sq. inches} \\ &= 7.38 \text{ sq. feet.} \end{aligned}$$

Hence, for a 1 inch diameter shothole in weak rock whose coefficient is $C_a = .008$,

$$F_1 = \frac{.032}{.008} \times 7.38 = 29.52 \text{ sq. feet.}$$

The sectional area of rock 29.52 sq. feet will offer the same resistance to rupture as the line of resistance for the shothole, which agrees with the formula $W = \frac{A}{C_{a1} S} = 4 \text{ feet } 9\frac{1}{2} \text{ inches}$, will offer to shearing.

On the other hand, it is evident that F varies as the square of the line of resistance, and as the line of resistance is proportional to the diameter d of borehole for any diameter of shothole, we can put

$$F = \frac{.032}{C_a} \times 7.38 d^2.$$

This formula is very useful in practice for determining the proper number of similar holes to rupture any given section of rock.

For example, it is required to blast a section of rock 26 feet long and 10 feet high, 8 feet back from the main face, the coefficient of the rock being .008 for dynamite, when the section is bounded by free faces, or joints offering no resistance.

The line of resistance being 8 feet, we can adopt holes of any diameter which will not shear a greater thickness of rock than 8 feet.

According to the formula $W = \frac{A}{C_a S}$, $1\frac{1}{2}$ inch diameter shotholes are equal to a line of resistance of 7 feet 2 inches, and we may, therefore, adopt holes of this or any smaller diameter according to the ballistic and shattering effect required.

For a $1\frac{1}{2}$ -inch diameter shothole, we have

$$F = \frac{.032}{.008} \times 7.38 \times (1\frac{1}{2})^2 = 66.42 \text{ sq. feet,}$$

that is to say, each $1\frac{1}{2}$ -inch shothole is equal to the rupture of a section of rock whose area is 66.42 sq. feet.

But the whole section to be ruptured is

$$26 \times 10 = 260 \text{ sq. feet.}$$

Consequently, the number of holes required is

$$\frac{260}{66.42} = 4 \text{ nearly.}$$

The holes should be placed, as shown in Fig. 27, in the lower bench to give the best effect, viz. perpendicular to the top face A B, and so that the distance of the end holes from the sides is equal to the line of resistance of the charges, viz. 7 feet 2 inches, and the centre holes equidistant from each other and the end holes.

The charge of dynamite required for each hole is 1·833 lb., being given by the formula $L = \cdot 5434 d^3$, Art. 60, page 80, and for the four holes $1\cdot833 \times 4 = 7\cdot332$ lbs.

The volume of rock blasted will be $26 \times 10 \times 8 = 2080$ cubic feet.

The chambers should be situated in the central part of section, and therefore the depth of each hole will be

$$\frac{10 + m}{2} = 5 \text{ feet } 9 \text{ inches.}$$

The section, however, may be blasted with fewer holes, if the length of charge and depth of hole be increased, since we have

$$\frac{F_1}{F} = \frac{A_1}{A} = \frac{S_1}{S}.$$

Supposing then that we make $A_1 = 2 A$, by doubling the length of charge it is clear that half the number of holes will suffice, and that they should have a depth of

$$\frac{10 + m}{2} = \frac{10 + 3}{2} = 6 \text{ feet } 6 \text{ inches.}$$

Economy in the boring of holes in this case is, therefore, attained by increasing the length of charge.

The two $1\frac{1}{2}$ -inch holes, 6 feet 6 inches deep, should be bored, as indicated in Fig. 27, in the upper bench.

Comparing the above with a case of stronger rock, as, for instance, when $C_a = .014$, then

$$F = \frac{.032}{.014} \times 7.38 \times (1\frac{1}{2})^2 = 37.96 \text{ sq. feet.}$$

And the number of $1\frac{1}{2}$ inch holes required if $m = 1$ foot 6 inches is

$$\frac{260}{37.96} = 7 \text{ holes.}$$

But experience shows that the length of charge may be one-half of the depth of hole under the given conditions. Therefore, if the holes be bored to a depth of 7 feet, the length of charge in each may be $\frac{7}{2}$ feet = 3 feet 6 inches, and there will be required for the work to be done

$$\frac{7 \times 1 \text{ foot 6 inches}}{3 \text{ feet 6 inches}} = 3 \text{ holes,}$$

instead of 7 holes as for the shorter length of charge 1 foot 6 inches. On the other hand, the total weight of charge will be the same for the seven as for the three holes viz. :

$$7 \times 1.833 \text{ lb.} = 3 \times 4.277 \text{ lbs.} = 12.831 \text{ lbs.}$$

The ballistic force of the blast for the same length of charge will be directly proportional to the square of the diameter of the boreholes. To reduce the same so as to just crack the rock from its bed, the diameter of the holes must be diminished.

For example, if 1-inch holes be used,

$$F = \frac{.032}{.014} \times 7.38 = 16.87,$$

and the number of holes of this diameter for a length of charge = 12 d = 1 foot is

$$\frac{260}{16.87} = 16 \text{ holes nearly,}$$

which number may be reduced to $\frac{16}{4} = 4$ holes by

making the length of charge 1 foot $\times 4 = 4$ feet.

A charge of dynamite 1 foot long in a 1-inch hole weighs .543 lb.; hence, the total weight of the charge will be

$$16 \times .543 \text{ lb.} = 4 \times 2.172 \text{ lbs.} = 8.69 \text{ lbs.}$$

There will, in consequence, be 8.69 lbs. to project the mass in this case, instead of 12.831 lbs. as in the other. In case there are no bedding joints, *e g m k*₁, and *g i o m*₁ (Fig. 27), the 1-inch and 1½-inch shotholes must be placed 2 feet 9 inches, and 4 feet 1½ inches (the lines of resistance for shearing) back from the free face A B.

63. *Length and Position of Charge for Shearing in Beds of Rock.*—In the case of beds of rock as

illustrated in Fig. 28, the lines of rupture produced by the explosion of the charge m , in the borehole, will evidently be limited by the bedding plane or joint $C D$, and if the joint $C D$ is an open one, we may assume that there is practically no resistance to the blast along $C D$. In this case, when the

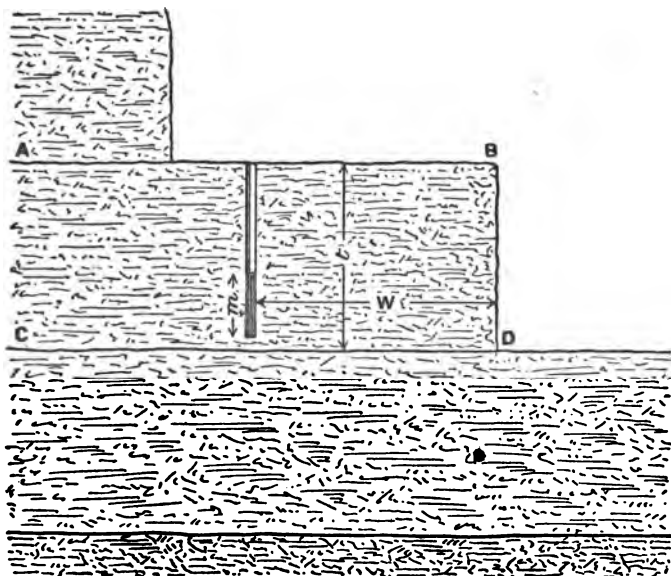


FIG. 28.

thickness t of the bed is less than $e W$ (W being the line of resistance if there were no joint $C D$), the length of charge should be proportioned to the relative resistance, which may be ascertained in the following manner.

In homogeneous rock, when there are no joints

or fissures, we have for the resistance to a blast $R = S W K_1 = e^2 W^2 K$, hence a section of rock whose section is $e^2 W^2$ may be a measure of the resistance of any shothole. On the same principle, the relative measure of the resistance to rupture when we are dealing with a bed of rock limited in thickness to less than $e W$, as shown in Fig. 28, if we denote the thickness of the bed by t , is $e W \times t$, which is evidently a smaller quantity than $e^2 W^2$. Therefore, the length of charge should be reduced so that the force of the blast is proportional to the resistance, as the force of a blast is proportional to the length of charge. Putting then m and m_1 as the lengths of charge required to overcome the resistances $e^2 W^2$ and $e t W$ we have

$$m : m_1 :: e^2 W^2 : e t W,$$

whence

$$m_1 = \frac{t m}{e W}.$$

For strong rock we have $e = 2$, and consequently,

$$m_1 = \frac{t m}{2 W}.$$

That is, when

$t = W$	$m_1 = \frac{1}{2} m$
$t = 1\frac{1}{4} W$	$m_1 = \frac{5}{8} m$
$t = 1\frac{1}{2} W$	$m_1 = \frac{3}{4} m$
$t = 1\frac{3}{4} W$	$m_1 = \frac{7}{8} m$
$t = 2 W$	$m_1 = m.$

If the joint C D is somewhat open it offers little or no resistance, and the proper position of the charge will be midway between the joint planes A B and C D. On the contrary, if the joint C D is tight the charge should extend to the same, and it should be adjusted between these limits according to the tightness of the joint C D, on the prin-

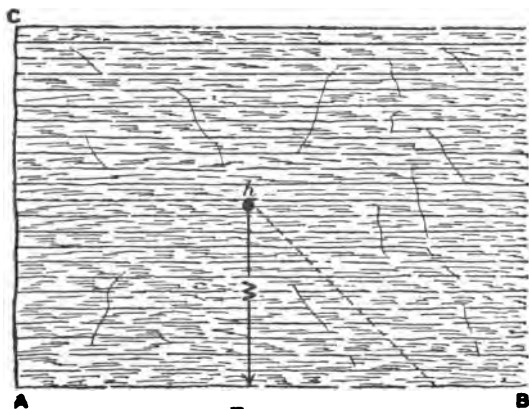


FIG. 29.

ciple that there should be equilibrium of resistance on all sides of the line of resistance.

When there are lateral free faces or joints we may place the charge a maximum distance W from the same when this is possible.

The charge should always be located in whole rock to prevent free escape of the gases and consequent reduction of the power of the blast. This rule, of course, only holds good when the strata are thicker than the length of the charge.